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Evaluation of the Virginia Department of Transportation Adaptive Signal Control Technology Pilot Project

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Abstract:

Currently, most traffic signals operated by the Virginia Department of Transportation (VDOT) use actuated plans that vary by time of day (TOD) and day of the week. These timing plans are typically developed off-line using traffic count information collected in the field and then processed using signal optimization software. This method works well as long as traffic volumes remain consistent with the conditions used to develop the timing plan, but timing plans can become suboptimal if traffic demands deviate from those conditions. Traffic growth over time, seasonal changes in traffic, special events, or incidents can all cause TOD plans to perform poorly, resulting in increased delays to drivers. As a result, VDOT must regularly retime signalized intersections to deal with long-term changes in travel patterns, which incurs costs to VDOT. Even so, non-recurring events can still cause TOD plans to perform poorly.

Adaptive signal control technology (ASCT) is one tool that has been proposed to handle variable traffic demand better. VDOT's Traffic Engineering Division began a pilot program to install the InSync ASCT developed by Rhythm Engineering on 13 corridors around the state beginning in 2011. The InSync system uses enhanced detection along a corridor to adjust signal timing parameters dynamically to meet observed demand in real time, eliminating the need to develop static timing plans. This allows the ASCT system to adjust signal timing parameters to account for variations in flow attributable to special events, seasonal flows, incidents, or simply the increase of volumes over time. In this case, signal timings are not pre-defined based on historic data, so ASCT systems can potentially reduce delays created by outdated static TOD plans.

These pilot deployments were evaluated to determine if ASCT created operational and safety improvements large enough to justify the additional costs to install ASCT. Data on mainline traffic operations, side street delays, and intersection crashes were collected with and without ASCT active. The results showed that mainline traffic operations generally improved if (1) the corridor was not oversaturated; (2) the corridor did not have characteristics that encourage platoon dispersion; and (3) the corridor did not already function well. Side street delays generally increased, although net benefits in overall corridor travel time were usually still observed. An empirical Bayes safety analysis of crashes at the intersections where ASCT was installed also found a 17% decrease in total crashes. Overall, ASCT generally produced a favorable benefit/cost ratio. The findings from the pilot tests were used to identify key considerations for future ASCT deployments so that VDOT could better identify future sites that might benefit from ASCT installation.

FINAL REPORT

EVALUATION OF THE VIRGINIA DEPARTMENT OF TRANSPORTATION ADAPTIVE SIGNAL CONTROL TECHNOLOGY PILOT PROJECT

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DISCLAIMER

ABSTRACT

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Adaptive signal control technology (ASCT) is one tool that has been proposed to handle variable traffic demand better. VDOT's Traffic Engineering Division began a pilot program to install the InSync ASCT developed by Rhythm Engineering on 13 corridors around the state beginning in 2011. The InSync system uses enhanced detection along a corridor to adjust signal timing parameters dynamically to meet observed demand in real time, eliminating the need to develop static timing plans. This allows the ASCT system to adjust signal timing parameters to account for variations in flow attributable to special events, seasonal flows, incidents, or simply the increase of volumes over time. In this case, signal timings are not pre-defined based on historic data, so ASCT systems can potentially reduce delays created by outdated static TOD plans.

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INTRODUCTION

Currently, most traffic signals in Virginia operate using actuated plans that vary by time of day (TOD) and day of the week. These timing plans are typically developed off-line using traffic count information collected in the field and then processed using signal optimization software. This method works well as long as traffic volumes remain similar to the conditions used to develop the timing plan, but timing plans can become suboptimal if traffic demands change. Traffic growth over time, seasonal changes in traffic, special events, or incident impacts can all cause TOD plans to perform poorly.

The Virginia Department of Transportation (VDOT) regularly retimes signalized intersections to address increased delays created by long-term changes in travel patterns, but regular signal retiming results in additional costs VDOT. Although retiming can alleviate delays created by long-term traffic growth, TOD plans still cannot easily deal with short-term variations in traffic demands attributable to incidents or special events. As a result, it has been estimated that 5% of all delay nationally is caused by poor signal timing (Cambridge Systematics and Texas Transportation Institute, 2005).

Adaptive signal control technology (ASCT) is one technique that has been proposed to process variable traffic demand at signals better. VDOT's Traffic Engineering Division (TED) began a pilot program to install the InSync ASCT developed by Rhythm Engineering on 13 corridors beginning in 2011. The 13 pilot corridors are listed in Table 1. The InSync system uses enhanced detection along the corridor to adjust signal timing parameters dynamically to meet observed demand, eliminating the need to define static TOD plans (Rhythm Engineering, n.d. a). This allows the InSync system to adjust signal timing parameters to account for

Table 1. InSync Pilot Corridors

Jurisdiction	Route	Activation Date	Predominant Cross Section	Length (mi)	No. of Signals	Average 2012 AADT	Predominant Speed Limit (mph)	Start/End Points
Fauquier	US 29	5/17/11	4-lane divided	9.4	6	43,932	55, with 45 mph section in midpoint	US 15 / US 17/30-880 (Lord Fairfax Dr / James Madison Hwy) to SR 215 (Vint Hill Rd)
Fairfax	SR 620 (Braddock)	7/30/11, removed 3/3/12	4-lane divided	1.6	5	37,844	40	Burke Station Rd to SR 123 (Ox Rd)
Frederick	US 11	8/15/11	4-lane divided	0.7	6	23,750	40	FR-733 (Crown Ln / Pactive Way) to Merchant St
Albemarle / City of Charlottesville	US 250	9/20/11	4-lane divided	2.0	8	34,730	45	High St / River Rd to I-64 EB off ramp
Frederick / City of Winchester	US 17/50/522	4/3/12	4-lane undivided	0.9	5	22,911	35	Mall Blvd to 34-797 (Prince Frederick Dr / Custer Ave)
Frederick	SR 277	4/ 17/12	2-lane undivided	1.4	7	13,147	35	US 11 to Warrior Dr
Frederick / City of Winchester	SR 7	5/7/12	4-lane undivided in city, 4-lane divided in county	2.3	12	23,834	35 in city, 45 in county	North Pleasant Valley Rd / National Ave to 34-656 (First Woods Dr)
York	US 17	6/19/12 (full deployment)	4-lane divided	7.2	19 (after full deployment)	39,924	45	99-634 (Old York-Hampton Hwy) to 99-704 (Cook Rd)
Augusta / City of Staunton	US 250	7/10/12	4-lane divided	1.8	10	22,654	35	Sangers Ln / Brand Station Rd to SR 261 (Statler Blvd)
Frederick / City of Winchester	US 50	11/6/12	4-lane divided	2.1	8	19,707	45 on western side, 35 on eastern side	National Lutheran Blvd to Fox Dr
Roanoke / City of Roanoke	SR 419 (Electric)	11/13/12	4-lane divided	2.0	9	33,624	45 to 35 mph	80-720 (Colonial Ave) to Penarth Rd
Campbell / City of Lynchburg	US 29	3/26/13	4-lane divided	5.8	11	34,794	35 in city, 45 in county	Glass Ave to 15-738 (English Tavern Rd)
York	SR 171 (Victory)	5/28/13	6-lane divided	1.1	5	42,418	45	Commonwealth Dr to SR 134 (Hampton Hwy)

AADT = average annual daily traffic.

variations in flow because of special events, seasonal flows, incidents, or simply increases in volumes over time. By adjusting signal timings "on the fly," the InSync system should eliminate the need for regular manual retiming. The system should also be able to adjust to short-term deviations from normal flow. Other ASCT systems have been shown to reduce delays and improve intersection efficiency in Virginia (Gartner et al., 2002) and elsewhere (Hutton et al., 2010), but InSync has not yet been evaluated in Virginia.

InSync uses traffic data collected using an internet protocol (IP) digital camera at each intersection, but these data can also be fused with existing vehicle detection (inductive loop detectors, video detectors, etc.) (Rhythm Engineering, n.d. a). The cameras process real-time images of traffic, and an algorithm is used to prioritize calls for green based on observed demands. The camera is connected via an Ethernet cable to the InSync processor, which is housed in the controller cabinet and is connected to the signal controller. The InSync processor can be installed with any signal controller model. Intersections are connected along a communications backbone so that information on approaching traffic demand can be communicated to adjacent intersections. Although the communications backbone is ideally a high bandwidth connection such as a fiber optic line, wireless communications can also be used. The InSync controller performs a global optimization along the corridor to provide green bands and a local optimization of individual signals. InSync does not operate with a fixed cycle length or phase order. Phases can be skipped or served multiple times per cycle depending on observed demands.

Although ASCT systems have been deployed in the United States and internationally, there are no clear guidelines as to when ASCT should be installed. The VDOT pilot program was instituted to gain insight into the types of corridors that might benefit from ASCT installation. VDOT's TED selected sites in consultation with the VDOT regions for inclusion in the pilot. Criteria that were considered in the initial site selection included the following:

- presence of variability in traffic patterns, including impacts of special events and non-recurring congestion
- heavy side street flows
- conflicts with other modes, such as pedestrians and transit
- support from local authorities.

The 13 corridors selected for the pilot project represented a range of geometric and traffic characteristics. Cross sections ranged from a two-lane undivided roadway on SR 277 to an eight-lane divided road on SR 171. Speed limits varied from 25 to 55 mph, and signal densities ranged from 0.64 to 8.57 signals per mile. The annual average daily traffic (AADT) varied from approximately 13,000 vehicles per day to approximately 44,000 vehicles per day.

VDOT's TED asked the Virginia Center for Transportation Innovation and Research (VCTIR) to evaluate whether InSync produced significant changes in operations and safety at the pilot sites. The results of this evaluation were to be used to determine whether future expansions to the program were warranted and to define what types of corridors were likely to benefit from ASCT in the future.

PURPOSE AND SCOPE

The purpose of this study was to assess the impact of the InSync pilot project on the 13 pilot corridors deployed around the state. Although InSync was the only ASCT system explicitly evaluated in this study, it was expected that many of the broad findings would be similar for other ASCT systems. As a result, InSync is referred to by trade name only where necessary. Specific results may or may not be transferable to other ASCT systems; however, it was expected that the basic trends would remain similar.

The objectives of the study were as follows:

1. Assess the impact of the ASCT system on mainline operations.
2. Determine the impact of the ASCT on side street operations.
3. Assess whether the ASCT system reduced crashes.
4. Provide guidelines, if possible, with regard to sites that are likely to benefit from ASCT installations in the future.

The scope of the study was limited to a field evaluation of the 13 pilot corridor sites. It should also be noted that the corridors were re-timed 3 to 5 years prior to the implementation of ASCT. The changes in operational performance noted in this study were due to a combination of improved ASCT operation and possibly outdated timing plans. However, no significant new development occurred in the immediate vicinity of any of the 13 pilot corridors before or during the study, so the researchers assumed that the timing plans functioned reasonably well prior to ASCT deployment.

METHODS

Review of the Literature

Previous evaluations of ASCT were identified using the TRID database and reviewed. The literature review focused on field and simulation evaluations of ASCT. The safety and mobility impacts of ASCT were reviewed. Case studies of the use of InSync were specifically reviewed to determine the past performance of the system.

Collection and Analysis of “Before” and “After” Operational Data at Pilot Locations

Four data sources were used to evaluate the operational performance of the pilot locations. The data sources used and their relevant measures of effectiveness (MOEs) were as follows:

1. *Floating car probe vehicle runs.* Data from global positioning system (GPS)-equipped floating car runs were collected at every site. These data were used to assess changes in mainline travel time, speed, and average number of stops. Because of the cost and staffing requirements of collecting floating car data, these data were collected for only 6 hr before and 6 hr after ASCT installation.

2. *Side street delay / queue length and traffic count information.* Side street delay or queue length data were collected at selected high-volume intersections along each corridor. Turning movement counts were also collected at these locations to determine if traffic volumes changed significantly between the periods before and after ASCT installation (hereinafter "before" and "after" periods). Because of cost and staffing concerns, these data were collected for 1 day before and 1 day after ASCT installation.

3. *Bluetooth travel time data.* At selected sites, Bluetooth travel time readers were installed to collect continuous travel time data on the mainline. This provided measures of 24-hr performance over a number of weeks at each site. This data source was available only at sites with a Bluetooth probe penetration large enough to generate reliable travel time estimates (see Table 2).

4. *Private sector travel time data.* VDOT has purchased probe travel time data from INRIX. Although the quality of the INRIX data has been established for freeways (Fontaine, 2013), the quality has not yet been validated for arterial roads. Since confidence in the absolute values of arterial travel times has not yet been defined, these data were used to examine relative performance before and after ASCT installation. These data were specifically used to examine travel time reliability since INRIX provided travel time data over a number of months. Although absolute accuracy has not been established, INRIX data should provide a reasonable measure of the relative impact of ASCT on reliability.

Table 2 shows which data sources were available at each site. The following sections describe the methods used to collect and analyze each of the operational data sources.

Floating Car Data

At every site, VCTIR collected floating car run data using GPS-equipped test vehicles. At each site, two to four probe vehicles would traverse a predefined circuit that encompassed the entire ASCT deployment and the approaches to the first signal in each direction. The floating car drivers were instructed to follow typical floating car procedures and approximate the average speed of travel while passing as many vehicles as passed them. Staggered start times were used to ensure approximately equal spacing of vehicles throughout the corridor. Each vehicle was equipped with a laptop running PC-Travel software and a USB GPS device. The software logged the position of the vehicle every second, and these data were later post-processed using PC-Travel to determine relevant MOEs. Mainline travel time and speeds and the number of stops were determined from these data. A stop was defined as any time the vehicle speed fell

Table 2. Data Availability at Pilot Sites

Jurisdiction	Route	Floating Car Data	Side Street Data	Bluetooth Data	INRIX Data
Fauquier	US 29	X	X		
Fairfax	SR 620 (Braddock)	X	X	X	X
Frederick	US 11	X	X		
Albemarle / City of Charlottesville	US 250	X	X		X
Frederick / City of Winchester	US 17/50/522	X	X	X	X
Frederick	SR 277	X	X		
Frederick / City of Winchester	SR 7	X	X	X	
York	US 17	X	X	X	X
Augusta / City of Staunton	US 250	X	X	X	X
Frederick / City of Winchester	US 50	X	X		X
Roanoke / City of Roanoke	SR 419 (Electric)	X	X	X	
Campbell / City of Lynchburg	US 29	X	X	X	X
York	SR 171 (Victory)	X	X		

below 3 mph. Thus, multiple stops could be recorded on the approach to an intersection if there were cycle failures and a probe vehicle did not proceed through the intersection.

Data were collected during the following time periods:

- morning peak (7-9 AM)
- midday peak (11 AM-1 PM)
- PM peak (4-6 PM).

Because of cost and staffing limitations, floating car data were collected at each site for 1 day before and 1 day after ASCT activation. In all cases, at least 1 month was allowed to elapse following ASCT activation before the after data were collected to ensure that the system reached equilibrium and to allow VDOT time to fine-tune the ASCT operation. The researchers also ensured that the before and after data were collected during the same season and checked school schedules and special events in the area to ensure that the data would be comparable.

It should be noted that the floating car sample sizes differed between the sites given the significantly different lengths of road being evaluated and levels of congestion (i.e., more travel time circuits could be completed on shorter / less congested roadways than longer / more congested roadways). Although more vehicles were used to collect data on these longer roadways, this difference was still present. In all cases, at least 15 travel time runs were completed per time period and direction during data collection. *T*-tests were conducted at each site at the 5% significance level ($\alpha = 0.05$) to determine whether there were statistically significant differences between performance measures at each site.

Side Street / Intersection Count Data

Data on side street operations were collected at a subset of intersections on each pilot corridor. Turning movement counts and side street delay / queue length information were collected at two to four intersections per corridor. The intersections were selected by VCTIR and VDOT's TED to focus on locations with high side street volumes and lower levels of service. As a result, the side street data analysis was focused on the intersections that were most likely to have degradations in performance.

Side street data were collected on the same dates as the floating car data by a private consultant. Video camera data were used to develop 12-hr turning movement counts for the major and minor streets. Field personnel determined side street delays in accordance with the methodology specified in the *Highway Capacity Manual* (HCM) (Transportation Research Board, 2010) for the same three time periods as for the floating car data. At some sites, the side street queues extended so far upstream of the intersection that field personnel could not view both the signal head and the end of the queue. In those cases, the field personnel measured the queue length in terms of vehicles or distance from the signal instead of the side street delay.

No statistical tests were conducted on these data since data were collected only 1 day before and 1 day after ASCT installation. Changes in turning movement volumes were examined to determine if volume conditions were comparable during both periods. The average delay per vehicle on the side streets was also assessed before and after ASCT installation.

Bluetooth Data

A limitation of the floating car data collection is that data were available only for the time periods when personnel were traversing the corridor. As a result, floating car data did not explicitly reflect how well ASCT responded during off peak periods, non-recurring congestion, or other times when information was not collected. In order to expand the time period that could be examined, VDOT's TED directed one of their contractors to install temporary Bluetooth travel time readers on selected corridors. Bluetooth readers log the unique media access control (MAC) addresses of Bluetooth devices that are in discoverable mode. By placing multiple readers along a corridor, it is possible to estimate the time to travel the section by examining the time stamps of MAC addresses that were logged by different readers. This method has the advantage of collecting data continuously once the readers are activated, but it also has several limitations. First, the readers provide information only on the travel time between two points, and information on what happens between the readers is not captured. Second, the quality of the travel times is driven by the number of Bluetooth probes that are detected at both readers. If the readers are spaced too far apart on an arterial, vehicles may leave the roadway at intermediate points. This could reduce sample size or introduce outlier speeds if those vehicles make a short stop and then rejoin traffic. As a result, the Bluetooth data must be examined to screen out outliers and determine if the remaining data are sufficient to generate reliable travel time estimates. Outlier screening was performed using the contractor's software algorithm, but the data still had to be checked to ensure that the sample size was sufficiently large to generate good estimates of mean performance.

Bluetooth data were accessed by downloading comma delimited text files from an online portal provided by the contractor. Approximately 1 month of data before and after ASCT installation were downloaded using 15-min aggregation intervals over the entire day for all the available corridor sections. First, the data were examined to determine if there were a sufficient number of vehicle probes to estimate a reliable travel time. Minimum sample sizes were defined based on the Central Limit Theorem using the following formula:

$$n = \left(\frac{z\sigma}{d} \right)^2$$

where

n = minimum sample size
Z = number of standard deviations corresponding to the required confidence level
σ = standard deviation of speeds (mph)
d = allowable error (mph).

For these data, a confidence level of 95% ($Z = 1.96$) and an error (d) of 5 mph were used to determine the required sample size. If the sample size requirement was not met, that interval was removed from the data analysis.

These data were then used to determine average travel times and speeds of the vehicles for the entire month, broken down into several time intervals: AM peak (7-11 AM), midday (11 AM-4 PM), PM peak (4-7 PM), early night (7-11 PM), and overnight (11 PM-7 AM). Since the Bluetooth data collection did not involve personnel collecting data continuously in the field, these time windows differ from the floating car data collection. The Bluetooth data collection periods were defined to fully capture the onset and dissipation of congestion across all sites. In contrast to the floating car data, the Bluetooth data allow for the performance of the system to be assessed over the entire day. Impacts of the system during non-recurring congestion can also be included in the assessment. In order to determine the effectiveness of the system, two-sample t-tests assuming unequal variances and $\alpha = 0.05$ were used to compare the before and after data for each interval.

INRIX Data

VDOT has contracted with the private company INRIX to provide probe-based speed and travel time information on major roadways in Virginia. INRIX generates estimates of speed and travel time by fusing commercial vehicle GPS, consumer GPS, and DOT sensor information (INRIX, 2013a). INRIX generates their estimates based on probe information collected anonymously from cars, trucks, taxis and many other types of vehicles as well as from GPS-enabled smart phones (INRIX 2013a, 2013b).

VDOT has access to real-time INRIX data statewide, and high-volume primary roads generally have INRIX coverage. Use of INRIX data has been validated in Virginia on the Interstate system (Fontaine, 2013), but there remain questions about its absolute accuracy on signalized primary roads. Despite the lack of a detailed validation of data accuracy on arterials, it was still examined in this analysis since relative comparisons could be made on a route, even if systematic bias exists. Since a long historic database of INRIX data exists, it was used only to assess relative changes in travel time reliability across corridors. Again, since the arterial data has not been validated, it was only used to assess an aggregate relative change in certain reliability measures across all sites where data were available.

The advantages of the INRIX data over other sources is that it provides 24-hr coverage, the data availability is often better than Bluetooth during low-volume periods, and data are available for a longer time period than even the Bluetooth data. Since INRIX had a long historic data set, it enabled researchers to make comparisons at the same site for the same seasons. This longer historic data set allowed for more stable reliability measures to be calculated than with Bluetooth data.

The Regional Integrated Traffic Information System web interface developed by the University of Maryland was used to collect travel time data in 15-min intervals. Since INRIX relies on probe vehicle information, data were typically available primarily for higher volume pilot locations. Three months of before and after data were downloaded for each site for which data were available. The start and end of the before and after time periods are shown in Table 3 for each site for which data were available. The before and after data were collected during the same months but 1 year apart to reduce the impact of seasonal variations in travel on the data.

The Braddock Road site was excluded from analysis even though data were available since corresponding seasons could not be compared because of system deactivation. The MOEs adopted for the analysis of INRIX data were the 95th percentile travel time and buffer index, both of which are measures of travel time reliability (Federal Highway Administration, 2006). The definition of *buffer index* is the extra travel time travelers must add when planning trips to ensure on-time arrival:

$$\text{Buffer Index} = \frac{95^{\text{th}} \text{ percentile travel time}}{\text{Average travel time}} - 1$$

Poor travel time reliability is often driven by non-recurring congestion. Since ASCT should theoretically be able to address non-recurring congestion better than traditional TOD plans, it was important to assess whether reliability was positively impacted by the system.

Table 3. Study Site Activation Dates and INRIX Analysis Periods

Location	Active Date	Before Start	Before End	After Start	After End
US 250, Albemarle/Charlottesville	9/20/11	2/1/11	4/30/11	2/1/12	4/30/12
US 17/50/522, Frederick/Winchester	4/3/12	2/1/11	4/30/11	2/1/13	4/30/13
US 17, York	6/19/12	2/1/12	4/30/12	2/1/13	4/30/13
US 250, Augusta/Staunton	7/10/12	2/1/12	4/30/12	2/1/13	4/30/13
US 50, Frederick/Winchester	11/6/12	2/1/12	4/30/12	2/1/13	4/30/13
US 29, Campbell/Lynchburg	3/26/13	6/1/12	8/31/12	6/1/13	8/31/13

Since the INRIX data rely on the presence of probe data, there may be periods when an insufficient number of probes traverse the section to generate a reliable travel time measure. During these periods, INRIX reports a travel time based off of historic data. This obviously is not useful when assessing the real-time performance of the ASCT system, so these data must be screened out. Each corridor is composed of multiple Traffic Message Channel (TMC) links, and a travel time is reported separately on each TMC. TMCs are defined by digital mapping companies such as NAVTEQ and Tele Atlas and typically span roadway sections between intersections. VDOT has specified that at least 85% of the TMCs composing a travel time corridor must be reporting real-time information before the data can be used for traveler information (VDOT, 2010). This threshold was checked for each discrete 15-min interval studied. For example, the US 17 corridor in York County is composed of 13 TMCs. At least $13 \times 0.85 = 11.05$, rounded up to 12, TMCs must report real-time information before the travel time data would be included in the evaluation. If fewer than 12 TMCs reported real-time data, that time interval would be discarded.

The data were then analyzed by time period. The INRIX data were segregated based on the following criteria: presence of ASCT (before and after), day of the week (Monday, Tuesday-Thursday, Friday, and weekends), and time of the day (morning, midday, afternoon, and night). Monday and Friday were separated from other weekdays because those two days are expected to have distinct traffic patterns. The *morning period* was defined as 6-10 AM, and the *afternoon period* was defined as 3-7 PM. The rest of the day was separated into a midday period and a nighttime period. As a result, there were $4 \times 4 = 16$ time periods for both the before and after scenarios. Differences between the before and after MOEs were then calculated by time period, and all differences were checked for statistical significance using a two-tailed paired *t*-test with $\alpha = 0.05$. Given that the arterial data have not been well-validated, these comparisons were conducted only across all sites to determine an aggregate relative impact on travel time reliability.

Analysis of Before and After Crash Data

An observational before and after study using the empirical Bayes (EB) approach recommended in the *Highway Safety Manual* (HSM) (American Association of State Highway and Transportation Officials [AASHTO], 2010) was conducted to examine the safety impact of ASCT at urban intersections. The EB method is able to account for regression-to-the mean effects, as well as traffic volume and other roadway and traffic control characteristics, by combining safety performance function (SPF) crash predictions with the observed crash counts (Hauer, 1997).

Crash data were analyzed for all intersections for which AADT information and at least 1 year of crash data after ASCT installation were available. Based on these criteria, 47 intersections on 10 corridors were investigated. Each of the tasks performed to conduct the EB analysis is described here.

Data Collection

Field data were collected from 47 intersections along 10 corridors where ASCT was installed. Each intersection was treated as a separate, independent site. Additional sites in each corridor had ASCT installed but were not analyzed because of missing minor road AADT information. These omitted sites were typically entrances to shopping centers or other low-volume roadways. Table 4 shows the number of ASCT intersections evaluated at each pilot site, the system activation date, and the durations of the before and after periods. In total, 235 site-years of before data (5 years per site) and 66 site-years of after data (1-2 years per site) were used in this analysis.

Major and minor road AADT data were collected from the VDOT Traffic Monitoring System, and crash data were collected from the VDOT Roadway Network System. Total crashes and fatal plus injury (FI) crashes were examined. All crashes reported within 250 ft of an intersection were considered as intersection crashes in this analysis. This distance range was selected to be consistent with that used by Garber and Rivera (2010) for the development of the Virginia-specific intersection SPFs. All other crashes were categorized as segment crashes and were not examined since arterial SPFs for Virginia were not available at the time of this analysis. Intersection characteristics, such as number of legs, presence of turn bays, and signal phasing data, were also collected.

Table 4. Intersection Sites Used in Safety Analysis

Corridor Name, Jurisdiction	No. of ASCT Intersections	Active Date	Before Period		After Period	
US 29, Fauquier	4	5/17/11	5/1/06-4/30/11	5 yr	6/1/11-5/31/13	2 yr
US 11, Frederick	5	8/15/11	8/1/06-7/31/11	5 yr	9/1/11-8/31/13	2 yr
US 250, Albemarle/ Charlottesville	6	9/20/11	9/1/06-8/31/11	5 yr	10/1/11-9/30/13	2 yr
US 17/50/522, Frederick/Winchester	3	4/3/12	4/1/07-3/31/12	5 yr	5/1/12-4/30/13	1 yr
SR 277, Frederick	5	4/17/12	4/1/07-3/31/12	5 yr	5/1/12-4/30/13	1yr
SR 7, Frederick/ Winchester	6	5/7/12	5/1/07-4/30/12	5 yr	6/1/12 -5/31/13	1 yr
US 17, York	8	6/19/12	6/1/07-5/31/12	5 yr	7/1/12- 6/31/13	1 yr
US 250, Augusta/ Staunton	3	7/10/12	7/1/07-6/30/12	5 yr	8/1/12-7/31/13	1yr
SR 419, Roanoke / City of Roanoke	5	11/13/12	11/1/07-10/30/12	5 yr	12/1/12-1/30/13	1 yr
US 50, Frederick/Winchester	2	11/6/12	11/1/07-10/31/12	5 yr	12/1/12-1/30/13	1 yr

ASCT = adaptive signal control technology.

Analysis Preparation

Virginia SPFs for Urban Intersections

A previous study developed SPFs for intersections in Virginia, using major and minor road AADT as predictor variables (Garber and Rivera, 2010). The SPFs were developed for both total crashes and combined fatal plus injury (FI) crashes through generalized linear modeling using a negative binomial distribution. In addition, separate models were developed for urban and rural intersections, as well as for the different regions of Virginia (Northern, Western, and Eastern) (Garber and Rivera, 2010). Regions were defined based on perceived differences in driving behavior and topography and subsequently went through a pruning process to consolidate models. Table 5 shows the recommended SPFs for signalized intersections in Virginia.

All the sites used in this study were classified as suburban or urban signalized intersections. Several base conditions for intersections are defined in the HSM (AASHTO, 2010) for use of national SPFs, and they are also applicable to Virginia SPFs:

- no left-turn lanes
- permissive left-turn signal phasing
- no right-turn lanes
- right-turn on red permitted
- no highway lighting
- no automated enforcement
- no bus stops, schools, or alcohol sales establishments near intersection.

Cases where the evaluation sites differed from these base conditions were determined, and appropriate crash modification factors (CMFs) were obtained from Part C of the HSM (AASHTO, 2010).

Table 5. Virginia Safety Performance Functions (SPFs) for Urban Signalized Intersections

Site		Virginia SPF Models to Be Used for Urban Intersections		Dispersion Parameter
Urban 4-legged signalized	Northern[a]	Total	$\exp(-7.6234 * MajADT^{0.6742} * MinADT^{0.3453})$	0.6481
Urban 4-legged signalized	Western	Total	$\exp(-12.3913 * MajADT^{0.631} * MinADT^{0.4567})$	0.9771
Urban 4-legged signalized	Eastern	Total	$\exp(-7.6234 * MajADT^{0.6742} * MinADT^{0.3453})$	0.5725
Urban 4-legged signalized	Northern	FI	$\exp(-8.5256 * MajADT^{0.6477} * MinADT^{0.3579})$	0.6463
Urban 4-legged signalized	Western	FI	$\exp(-11.4284 * MajADT^{0.8662} * MinADT^{0.4412})$	0.7947
Urban 4-legged signalized	Eastern	FI	$\exp(-9.9582 * MajADT^{0.7484} * MinADT^{0.4017})$	0.5828
Urban 3-legged signalized	Northern	Total	$\exp(-6.5430 * MajADT^{0.6591} * MinADT^{0.2119})$	0.6708
Urban 3-legged signalized	Western	Total	$\exp(-9.6143 * MajADT^{0.8677} * MinADT^{0.3297})$	0.8647
Urban 3-legged signalized	Eastern	Total	$\exp(-6.5430 * MajADT^{0.6591} * MinADT^{0.2119})$	0.7576
Urban 3-legged signalized	Northern	FI	$\exp(-8.4268 * MajADT^{0.7147} * MinADT^{0.2481})$	0.7641
Urban 3-legged signalized	Western	FI	$\exp(-11.0104 * MajADT^{0.9080} * MinADT^{0.3226})$	1.0307
Urban 3-legged signalized	Eastern	FI	$\exp(-8.4268 * MajADT^{0.7147} * MinADT^{0.2481})$	0.6564

FI = fatal plus injury crashes.
[a] Garber and Rivera (2010) divided Virginia into three regions, Northern, Western, and Eastern, and developed region-specific SPFs. The SPFs in this table were taken from their study.

Determination of Predicted Crashes

After the Virginia SPFs were applied to determine the base number of predicted crashes, Equation 1 was applied to determine the adjusted predicted crash frequency that corresponded to the characteristics of a specific intersection.

$$N_{predicted} = N_{spf} \times (\mathrm{CMF}_{1x} \times \mathrm{CMF}_{2x} \times ... \times \mathrm{CMF}_{yx}) \qquad \text{[Eq. 1]}$$

The EB method recommended in the HSM was used to develop a CMF for installation of ASCT. Chapter 9 of the HSM (AASHTO, 2010) provides the computational procedure for implementing the EB before and after safety effectiveness evaluation method. The steps used to perform this analysis are briefly described here.

Step 1. Use the Virginia intersection SPFs and HSM CMFs to calculate the predicted average crash frequency using Equation 1 for the before and after periods at each site. Apply the EB correction using observed data to calculate the expected average crash frequency in the before period using Equation 2.

$$N_{\mathrm{exp}ected,B} = w_{i,B} N_{predicted} + (1 - w_{i,\mathrm{B}})\,\mathrm{N}_{observed,B} \qquad \text{[Eq. 2]}$$

where

the weight, $w_{i,B}$, for each site i, is determined as

$$w_{i,B} = \frac{1}{1 + k \sum_{\substack{Before \\ years}} N_{predicted}}$$

and

$N_{predicted}$ = expected average crash frequency at site i for the entire before period using the applicable SPF

$N_{observed,B}$ = observed crash frequency at site i for the entire before period

k = overdispersion parameter for the applicable SPF.

Step 2. Calculate adjustment factors r_i for both Total and FI crashes to account for the differences between the before and after periods in duration and traffic volume at each site i using Equation 3. Use Equation 4 to calculate expected average crash frequency, $N_{Expected,A}$, for each site i, over the entire after period in the absence of the treatment.

$$r_i = \frac{\sum_{\substack{After \\ years}} N_{predicted,A}}{\sum_{\substack{Before \\ years}} N_{predicted,B}}$$ [Eq. 3]

$$N_{expected,A} = N_{expected,B} \times r_i$$ [Eq. 4]

where

$N_{observed,A}$ = observed crash frequency at site i for the entire after period.

Step 3. Calculate the overall effectiveness of ASCT, expressed as a CMF, using Equation 5. Equation 6 is then used to translate the CMF into an estimated safety effectiveness. In addition, calculate the standard error of the estimated CMF using Equation 7, indicating the stability of the estimated CMF.

$$CMF = \frac{\sum_{All\ Sites} N_{Observed,A} \Big/ \sum_{All\ Sites} N_{Expected,A}}{1 + \sum_{All\ Sites} \left[(r_i)^2 \times N_{Expected,B} \times (1 - w_{i.B}) \right] \Big/ \left(\sum_{All\ Sites} N_{Expected,A} \right)^2}$$ [Eq. 5]

$$\text{Safety Effectiveness} = 100 \times (1 - CMF)$$ [Eq. 6]

$$\sigma = \sqrt{\frac{\left(\frac{\sum_{All\ sites} N_{observed,A}}{\sum_{All\ sites} N_{expected,A}} \right)^2 \left[\frac{1}{N_{observed,A}} + \frac{Var(\sum_{All\ sites} N_{expected,A})}{(\sum_{All\ sites} N_{expected,A})^2} \right]}{\left[1 + \frac{Var(\sum_{All\ sites} N_{expected,A})}{(\sum_{All\ sites} N_{expected,A})^2} \right]}}$$ [Eq. 7]

To test the statistical significance of the analysis result, the following rules are used in the HSM (AASHTO, 2010):

- If Abs[Safety Effectiveness/σ] < 1.7, conclude that the treatment effect is not significant at the (approximate) 90% confidence level.

- If Abs[Safety Effectiveness/ σ] ≥ 1.7, conclude that the treatment effect is significant at the (approximate) 90% confidence level.

- If Abs[Safety Effectiveness/ σ] ≥ 2.0, conclude that the treatment effect is significant at the (approximate) 95% confidence level.

Benefit/Cost Analysis

A benefit/cost (B/C) ratio was computed for each site to assess whether the ASCT deployment produced an overall net benefit. VDOT's TED provided costs associated with the initial purchase and installation of ASCT. This included costs for ASCT processors, detection upgrades, and communications upgrades prior to ASCT activation. Although it would have been desirable to quantify ongoing maintenance costs associated with the system deployment, these data could not be isolated easily and were not included. Inclusion of maintenance costs would have likely reduced the B/C ratios from those presented in this report, so the B/C ratios shown are likely to be optimistic.

Changes in user delays on the corridor were determined and monetized, although the methodology used to do this varied depending on the data available at a particular site. Values of time from the *2012 Urban Mobility Report* (Schrank et al., 2012) were used to monetize user delays for both passenger cars and trucks. The following equation was used to determine the user delay savings:

$$User\ Delay = \sum_{i=1}^{24} \left\{ \frac{\left(TT_{before} - TT_{after}\right)}{3600} \times [AADT \times HourlyVolumePct \times (\%Truck \times TruckVOT + (1 - \%Truck)CarVOT)] \right\}$$

where

TT_{before} = average travel time before ASCT installation for hour *i* (sec)

TT_{after} = average travel time after ASCT installation for hour *i* (sec)

HourlyVolumePct = percent of AADT on section occurring in hour *i*

% Truck = percentage of trucks on section

Truck VOT = truck value of time, taken as $86.81/veh-hr, from the *2012 Urban Mobility Report* (Schrank et al., 2012)

CarVOT = car value of time, taken as $20.99/veh-hr, from the *2012 Urban Mobility Report* based on an assumption of 1.25 people per car (Schrank et al., 2012).

The VDOT Traffic Monitoring System (TMS) was used to determine the proportion of AADT that occurred during each hour of the day at each site based on historic information since real-time, continuous volume data were not available at most locations. The TMS data were used to develop typical daily profiles using the data available to determine HourlyVolumePct. Likewise, the TMS data were used to determine the average percentage of trucks and AADT on each section studied.

The source of the mainline travel time data before and after installation of ASCT varied depending on the data available. If continuous Bluetooth travel time data were available, they were used to determine an average travel time for each hour before and after ASCT installation. When Bluetooth data were not available, floating car data from the AM peak, midday, and PM peak were used instead. In order to be conservative, if floating car data were used, it was assumed that there was no difference in travel times between the before and after periods during time periods when data were not collected. Regardless of the data source, user delay changes were quantified only for time periods when the earlier statistical tests revealed statistically significant changes in mean performance. If differences were not statistically significant, it was assumed that the difference between the before and after periods was equal to zero. This was done to generate a conservative estimate of the system impacts.

Delay information on side street approaches was sparse, and quantification of side street delay impacts had more assumptions. The only data available on side street delays were collected at the same time as the floating car data. Data were typically available only at two to four high-volume intersections, and that delay information coincided with only the AM, midday, and PM weekday peak periods. First, to be conservative, it was assumed that there was no change in delay for any time periods where delay data were not explicitly collected. Second, it was assumed that average delay changes at the two to four intersections where data were collected could be extrapolated across remaining side street approaches where no data were available. Although this assumption is obviously imprecise, it at least attempts to create a planning level estimate of potential impacts.

Finally, estimated safety benefits of the system were monetized using the CMF results. Crash costs were defined using the values in place for the VDOT Highway Safety Improvement Program (HSIP) (VDOT, 2012).

Development of Considerations for Future Deployments

The results for the before and after periods were synthesized and contrasted against site characteristics to determine if any guidelines for ASCT installation could be generated. Site characteristics including AADT, signal density, access point density, and site cross section and geometry were examined to determine if there were identifiable trends in performance as a function of these factors by calculating correlation coefficients. In addition, lessons learned from field experience during the pilot deployment were documented. It was hoped that the outcome of this task would help guide future site selection and implementation decisions related to new ASCT investments.

RESULTS

Literature Review

Overview of ASCT

ASCT systems adjust signal timings dynamically based on the observed traffic flow at a site. There are two main types of ASCT systems: traffic responsive and real-time adaptive (Stevanovic, 2010). Traffic responsive ASCT systems collect traffic data over several minutes and send the data to an off-site location for analysis. The software at this location compares the data to various predetermined timing plan options based on preset parameters. Once an option is selected, the computer sends the new signal timings to the field for implementation. One of the major disadvantages of traffic responsive ASCT is that it takes time to analyze and implement signal timing changes, so the new timings may fall behind current traffic demands. Real-time ASCT uses more complex algorithms to develop timing plans dynamically, has no lag time, and has the ability to calculate signal timings on-site (Siromaskul and Selinger, 2010). InSync is an example of a real-time adaptive system.

ASCT requires additional hardware and detection beyond that required for traditional actuated signals (Stevanovic, 2010). Although requirements vary depending on the ASCT vendor, additional detection, communications infrastructure, and controller hardware and software must typically be installed. Thus, use of ASCT typically increases costs over that of an actuated signal. Often, ASCT systems will require stop-line detectors; near stop-line detectors; upstream (mid-block) detectors (which can be used to estimate long queue lengths); and downstream (far-side) detectors, which are located at the exit point of the intersection. The type of detection required is influenced by the ASCT control logic used with a particular system. Stop-line detectors typically have a delay when implementing a new timing schedule, whereas upstream detectors allow ASCT to operate in a more predictive manner (Stevanovic, 2010).

There are three primary ways in which an ASCT system may operate. The first is domain-constrained optimization (Stevanovic, 2010). This method is focused on preventing large fluctuations in traffic volume. The second is time-constrained optimization, which includes restrictive time and structural boundaries that are implemented by local controller policies. The third is rule-based adjustment, which captures any method used to develop a relationship between change in traffic conditions and the resulting timing changes (Stevanovic, 2010).

Historical Development of ASCT

ASCT was first explored during the 1970s, but the traffic-responsive pattern selection systems that were being used could not efficiently handle fluctuations in traffic flow (Stevanovic, 2010). At that time, ASCT systems were not heavily pursued because it was commonly believed that the use of multiple TOD plans would be sufficient to deal with variations in flow (Stevanovic, 2010).

The first commonly deployed ASCT systems were the Sydney Coordinated Adaptive Traffic System (SCATS) and the Split Cycle Offset Optimization Technique (SCOOT), which were developed in Australia and the United Kingdom, respectively (Stevanovic, 2010). These systems used various algorithms to determine signal timing instead of preset intervals. Soon after, the United States launched a modified version of Optimization Policies for Adaptive Control (OPAC) and Real-Time Hierarchical Optimized Distributed and Effective System (RHODES) ASCTs. Although these systems were proven to be effective, they were not widely deployed because of the increased cost of operations and maintenance, extensive detection requirements, necessary hardware upgrades, complexity of their logic, and personnel training requirements (Stevanovic, 2010).

In 2010, there were approximately 25 ASCT systems in use in the United States, and more recently technological developments have focused on how to make the systems less expensive and more user-friendly (Stevanovic, 2010). Older ASCT systems (SCOOT, SCATS, OPAC, RHODES) were largely concentrated in California and Florida and operated by local agencies. Many localities choose to install the systems for one of two reasons. First, it was believed that ASCT would eliminate the costs associated with retiming signals every 3 to 5 years. Second, it was expected that these systems would alleviate congestion through more responsive signal timing (Stevanovic, 2010).

General Considerations for Installation of ASCT

Although ASCT is a conceptually appealing way to operate a signal system, the additional expense of installing ASCT may not be justified in cases where traditional TOD plans function adequately. ASCT is generally considered to be effective in areas where traffic demand is variable, making it difficult for TOD plans to react to observed demand (Federal Highway Administration, 2012).

Before installation of ASCT, agencies should weigh potential reductions in traffic congestion, emissions, and crashes versus the financial costs to construct and maintain the system. ASCT can require a significant amount of capital for initial installation, from $30,000 to $80,000 per intersection depending on existing equipment and conditions (Sprague, 2012). There is a variety of costs that need to be considered for an installation, including licensing of the devices, warranty, hardware, servers, processors, communications, and detectors, among others (Federal Highway Administration, 2012). In addition, maintenance costs need to be accounted for. Agencies responsible for running the systems need to have properly trained staff to fix any issues that may arise and to perform regular maintenance. In a survey conducted for a recent National Cooperative Highway Research Program (NCHRP) synthesis, approximately 60% of adaptive traffic control system users said that maintenance is more demanding on ASCT systems than on traditional signal systems, and some said it was difficult to learn the new system (Stevanovic, 2010). Further, the majority of agencies using ASCT said that they would use the same system in the future at a new site. However, those who said they would not use ASCT again frequently cited maintenance costs as a major barrier to continued use (Stevanovic, 2010). Other issues ASCT users mentioned in the survey included a lack of training by the vendors in operating the system, insufficient local planning, and inadequate infrastructure preparation (Stevanovic, 2010).

Although maintenance costs are often cited as a significant issue with ASCT installation, the NCHRP synthesis reported that the cost of maintaining an ASCT system was approximately 75% of what was spent to maintain signal timings for traditional systems (Stevanovic, 2010). Traditional TOD plans must be regularly re-optimized to ensure adequate performance, which requires that the transportation agency collect turning movement counts and develop new timing plans (Federal Highway Administration, 2013). Ultimately, this process of updating signal timing plans can be time-consuming and requires regular adjustments every few years in order to ensure that the timing plans remain up to date with current traffic volumes along the corridor. Because of budget constraints, departments of transportation may defer updating traffic signal timing plans, which can result in increased delays along the corridor (Selinger, 2010).

InSync ASCT

The operational impact of ASCT systems has been evaluated in a number of studies. As stated previously, the InSync system was deployed on the VDOT pilot corridors. InSync is a real-time adaptive signal system that adjusts the signal timing to adjust to observed traffic demands on the corridor. InSync connects directly into existing signal hardware, collecting data to analyze changing traffic patterns along a roadway and adjust signal timings (Sprague, 2012). First, speed and volume data are collected and sent to a processor. Second, the processor communicates these data to other intersection processors along the specific roadway corridor. Third, by working together, all intersection processors determine offsets in order to allow steady flow along the entire length of the main road (Sprague, 2012). In order to prevent phasing sequences that would disrupt the flow of the traffic along the main corridor, agencies can program certain preferences into the system. The InSync systems will then take these preferences and combine them with the detector data, adjusting the timings to real-time conditions. These timings and phases are easily changed based on the current traffic demand of the roadway (Sprague, 2012).

The performance of InSync has been evaluated at several locations. Previous independent evaluations of InSync are briefly reviewed here.

Route 291 in Lee's Summit, Missouri

In the spring of 2009, the Missouri Department of Transportation (MoDOT) installed InSync along Route 291 in Lee's Summit. MoDOT hired the Midwest Research Institute to perform an independent evaluation of the system (Hutton et al., 2010). A before and after study was conducted to evaluate the impact of the system. MOEs used were travel time, delay, vehicle emissions, fuel consumption, and number of stops. Volume data were also collected to ensure that volume changes did not influence the MOEs (Hutton et al., 2010).

The study found that travel times generally improved. In instances where the travel time was reduced, the number of stops, fuel consumption, and emissions were also reduced. Volumes both before and after implementation of the InSync software varied only slightly, meaning that any changes in travel times and delay were not a result of changes in traffic volume. Although the overall delay for the mainline roadway decreased, results showed that minor street delays increased (Hutton et al., 2010).

The researchers concluded that InSync was effective in reducing travel time, delay, emissions, fuel consumption, and number of stops (Hutton et al., 2010). Although there was a slight increase in the delay on the minor streets, there was a net positive effect on the entire corridor (Hutton et al., 2010).

Crow Canyon Road and Bollinger Canyon Road in San Ramon, California

The InSync system was installed along two separate corridors (Crow Canyon Road and Bollinger Canyon Road) in San Ramon, California, in August 2010. DKS Associates was hired to conduct a before and after study of the performance of InSync on these corridors (DKS Associates, 2010). Data from GPS-equipped floating car runs were collected in both directions along the corridor during four TOD periods (7-9 AM, 9-11 AM, 11:30 AM-1:30 PM, and 4:30-6:30 PM) before and after InSync was installed (DKS Associates, 2010). Minor street delays were also measured using the HCM methodology at two selected intersections during the same time periods that floating car data were collected (DKS Associates, 2010). Traffic volume data were also collected during the same time periods where delay and travel time data were collected.

The MOEs used for the floating car data were similar to those used in the MoDOT study (DKS Associates, 2010). Results from these studies showed some variability, but overall InSync provided an improvement over the existing signal system. The largest decrease in average travel time (73.2 sec [50.2%] during the PM peak) occurred along Bollinger Canyon Road in the westbound direction. The average major approach delay improved by as much as 61.1 sec (74.8%) during the PM peak along the same corridor. Overall, the average travel times and major approach delay for both corridors improved for every TOD period except for the PM peak in the eastbound direction at both corridors. This increase in congestion during the PM peak may be attributed to increased traffic demands along each corridor at this specific time period versus the before period (DKS Associates, 2010).

Although the average vehicle delay along the major road decreased, the average vehicle delay along the minor streets increased by approximately 3 sec per vehicle. Since this difference was relatively small, the researchers concluded that the benefits of decreased delay along the mainline outweighed the costs of increased delay along the side streets (DKS Associates, 2010).

10th Street Corridor in Greeley, Colorado

InSync was installed at 11 intersections along 10th Street in Greeley, Colorado (Sprague, 2012). The evaluation corridor had an AADT of 25,000 to 28,000 vehicles per day and was 4 mi long. Atkins Consulting conducted an independent evaluation of the system. Floating car runs were used to collect data on mainline travel time, fuel consumption, and average number of stops. Side street delays were also collected from video data using the HCM methodology.

The evaluators found that InSync improved travel times by 9%, reduced stopped delay by 13%, and increased average speed by 11% on weekdays. Fuel consumption and emissions were expected to improve by 3% to 9%, and stops were reduced by 37% to 52%. As in prior studies, side street delays increased on some approaches. However, when increased side street delays were combined with decreased mainline delays, the researchers estimated an average net reduction of 166 veh-hr of delay per day. When reductions in fuel consumption and improvements in delay were considered, the researchers concluded that the site was associated with an annual benefit of about $1.3 million per year. When compared to the initial installation cost, the project had a B/C ratio of approximately 1.58 based on just 1 year of performance (Sprague, 2012).

Other Case Studies

Rhythm Engineering documented results for several other case studies, but no independent evaluations of these sites could be identified (Rhythm Engineering, n.d. b). Table 6 summarizes those results, but they have not been independently confirmed.

Table 6. Additional InSync Case Studies

Location	Increase in Average Speed	Reduction in Stops	Reduction in Delay	Reduction in Travel Time	Reduction in Fuel Consumption	Reduction in Emissions
Columbia, Mo.	41%	90%	77%	29%	16%	25%
Evans, Ga.	93%	75%	78%	48%	32%	39%
Grapevine, Tex.—Bass Pro Dr, NW Hwy, St Hwy 26	84%, 71%, 35%	70%, 71%, 88%	70%, 76%, 81%	45%, 42%, 26%	31%, 28%, 11%	29%, 40%, 19%
Salinas, Calif.	84%	91%	89%	46%	-	-
Springdale, Ark.	73%	95%	86%	42%	26%	35%
Topeka, Kans.	96%	100%	78%	49%	36%	47%
Upper Merion, Pa.	35%	86%	76%	26%	28%	30%
Wichita, Kans.	78%	100%	89%	44%	28%	42%

Source: Rhythm Engineering (n.d. b).

Safety Impacts of ASCT

Although ASCT is usually installed to improve operations, reductions in mainline stops and delays could translate into safety improvements. To date, very few studies have evaluated ASCT safety impacts using field data. Hicks and Carter (2000) found that ASCT reduced the number of stops by 28% to 41% and hypothesized that the reduction in stops may lead to a reduced chance of rear-end crashes. Anzek et al. (2005) investigated the impact of converting a signalized intersection from pre-timed phasing to a simple adaptive traffic control and observed a 35% reduction in the number of crashes after the conversion. However, this study was based on only a 1-year before and after period at a single intersection. Dutta et al. (2010) applied data from an ASCT test bed in Oakland County, Michigan, to analyze the safety benefits of SCATS. They observed a shift in the severity of crashes from Type A (incapacitating injury, permanent injury) and Type B (non-incapacitating injury, temporary injury) to Type C (possible injury, slight bruises and cuts). However, the reductions were not statistically significant at the 95% confidence level. Midenet at al. (2011) investigated exposure to lateral collisions at signalized intersections for two traffic control strategies: a real-time adaptive traffic control strategy called CRONOS and a traditional vehicle-actuated timing plan strategy. The results of case studies of an isolated intersection in Paris showed that CRONOS reduced the total time exposure to lateral collisions under peak hour traffic conditions by roughly 5 min/hr.

Several studies have also used microscopic simulation to evaluate the safety effects of ASCT, typically through the use of surrogate safety measures. Stevanovic et al. (2011) used a microsimulation model connected to SCATS to generate vehicular trajectories that were fed into the Surrogate Safety Assessment Model (Gettman and Head, 2003; Gettman et al., 2008). The results showed that the ASCT simulation generated fewer rear-end and total conflicts but more crossing and lane changing conflicts than the traditional control. However, the simulated conflicts and field crashes did not correlate well. Sabra et al. (2010, 2013) developed a crash prediction model (SPF) using neural networks with field data from ASCT and actuated signals. After training the network with approximately 150 signal timing scenarios, the crash prediction method used in the studies (Sabra et al., 2010, 2013) produced an average traffic conflict prediction error for ASCT cases not used for training of 17%. The studies found that it was difficult to estimate field crash data accurately using a simulation approach. In addition to the underlying uncertainty in relating crash surrogates to crash frequency, many ASCT systems cannot be easily simulated using commercially available microsimulation packages. ASCT vendors often are reluctant to make information on how their system works publicly available, which further limits the ability to evaluate ASCT through microsimulation.

Summary of Previous Research

In summary, previous evaluations of ASCT have generally shown improvements in mainline traffic flow but small increases in side street delays. Net benefits of the system were generally perceived to be positive. One common limitation of all the studies, however, is that they looked at only a relatively narrow time window, often only 1 day of data before and 1 day of data after installation. Where feasible, this study used multiple days of data collected along the mainline using Bluetooth and INRIX data to determine if the benefits noted in previous studies were sustained over time at the VDOT pilot sites.

Potential crash reduction benefits of ASCT have also not been clearly defined. Simulation-based safety evaluations are often limited by incomplete models of the adaptive signal performance, and current empirical studies usually suffer from limited data and rely on naïve before and after evaluations. There is a need for more rigorous examination of ASCT safety effects by using increasingly available data and more robust evaluation techniques.

Before and After Study of Traffic Operations

This section discusses the operational changes for each corridor as a result of the installation of ASCT.

Traffic Volume Changes

As stated previously, volume changes between the before and after periods at the study sites were examined to ensure that changes in operations were not related to large shifts in traffic demand. Changes in traffic volumes between the before and after periods are summarized in Table 7 for the intersections where turning movement data were collected. On average, volume increased +2.4% between the before and after period. Percentage changes in volumes were generally fairly small.

Table 7. Average Change in Traffic Volumes on Pilot Corridors

Jurisdiction	Route	Intersections Evaluated	Average % Volume Change by Time of Day			
			AM	Midday	PM	Average
Fauquier	US 29	Lord Fairfax	-2	-2	-4	-3
		Dumfries	-4	-3	-4	-4
		Beverly Mills / Broad Run Church	-9	-3	-2	-5
Fairfax	SR 620 (Braddock)	SR 123	0	-1	-2	-1
		Sideburn/Mattaponi	+1	-6	-4	-3
		Roberts	+1	0	+1	+1
Frederick	US 11	Amoco/Welltown	-3	0	+6	+1
		Snowden Bridge / Merchant	+2	+7	+13	+8
Albemarle / City of Charlottesville	US 250	I-64 EB	+1	+7	+1	+3
		River/High	+5	+3	+6	+5
		Rolkin	+2	+7	0	+3
Frederick / City of Winchester	US 17/50/522	Custer / Prince Frederick	+1	+1	+8	+3
		Frontage Rd / Bob Evans	-9	-7	+24	+3
		I-81 NB ramp / Front Royal	-3	+2	+7	+4
		I-81 SB ramps	-2	0	+7	+2
Frederick	SR 277	Aylor / Town Run	+8	+2	+5	+4
		I-81 NB ramps	+3	0	+6	+3
		I-81 SB ramps	+1	+3	0	+1
Frederick / City of Winchester	SR 7	Fort Collier / Elm	+7	+12	+7	+9
		Gateway	+9	+2	+8	+6
		I-81 NB ramp	+10	+12	+10	+11
		I-81 SB ramp	+4	+6	+3	+4
York	US 17	Denbigh	+10	+3	-2	+4
		Wolf Trap / Armory	+31	+7	+10	+16
		Lakeside/Oriana	+11	-7	-7	-1
		Coventry	+1	+10	-1	+3
Augusta / City of Staunton	US 250	Statler	0	+8	+1	+3
		Frontier	-2	+4	+2	+1
		I-81 SB ramp	+2	+10	+2	+5
Frederick / City of Winchester	US 50	Round Hill	+5	+1	+2	+3
		SR 37 NB ramp	+3	-4	-2	-1
		Westside Station	+1	-5	-3	-3
Roanoke / City of Roanoke	SR 419 (Electric)	Tanglewood	-3	-8	+3	-2
		Ogden	0	-4	+6	+1
		Starkey	-2	-8	+3	-2
Campbell / City of Lynchburg	US 29	Lawyers	-5	-2	+10	+1
		Old Wards Rd	+1	+2	+3	+2
		Wards Ferry	0	+6	+9	+5
York	SR 171 (Victory)	Kiln Creek	+3	+10	-7	+2
		SR 134	-6	+18	-1	+4

The data show that in 35 of 40 (87.5%) intersections, volumes changed by ±5% or less, and in 25 of 40 (62.5%) intersections, there were volume changes of ±3% or less. Overall, in 75% of the sites, volumes increased, averaging +4.0%. The 25% of sites with decreased volumes showed an average decline of -2.5%. Given these data, it is expected that, if anything, the estimates of mainline performance and side street delay results in the after period would tend to be conservative given the overall trend of increasing volume. On average, volumes increased in the after period at the majority of sites, so this would mitigate some of the potential operational benefits of the system.

Number of Mainline Stops Based on Floating Car Data

Table 8 shows the change in the average number of stops per one-way traversal of each corridor's mainline after ASCT was activated based on floating car data. Negative numbers represent reductions in the number of stops, whereas positive numbers represent increases in the number of stops following ASCT activation. A *stop* was defined as a single instance when the probe vehicle's speed dropped to below 3 mph. It is possible for a probe vehicle to record multiple stops at a single signal if there are cycle failures and the probe fails to clear the intersection. Differences in stops were compared using a *t*-test with $\alpha = 0.05$ for each time period. Values in italics had a statistically significant change in only one direction of travel, whereas values shown in bold and italics had a statistically significant difference in both directions. In total, 78 comparisons were made using *t*-tests (3 times of day × 2 directions per site × 13 sites). Of these 78 comparisons, 62 comparisons (79.5%) had a statistically significant change in the average number of stops per one-way traversal of the corridor.

Only 6 of the 78 comparisons (7.7%) found a statistically significant increase in stops, whereas 56 of the 78 comparisons (71.8%) found a statistically significant reduction in stops. Table 8 shows that for only a few sites was there a statistically significant increase in mainline stops after ASCT activation. At US 11 in Frederick County, the number of stops increased significantly in both directions during the AM and midday periods, whereas the number of stops increased significantly in the NB direction and decreased significantly in the SB direction in the PM period. Stops also increased significantly in the NB direction of US 17 in York County. At sites with a reduction in stops, average reductions across time periods ranged from 14% to more than 61%. The large magnitudes of reductions in stops may translate into safety benefits since there would be fewer opportunities for human error during the stopping maneuver.

Increases in stops at the US 11 site in Frederick County were likely partially attributable to how the corridor was progressed with the ASCT system. An interchange with I-81 was located on the eastern end of the corridor, and traffic was coordinated so that a green band would be provided for traffic turning left off of the I-81 NB off ramp traveling to US 11 SB. By coordinating with the off ramp movement, this impaired progression along mainline US 11. Additional issues on this corridor included the relatively high truck percentage (8% trucks). The large trucks were slower to accelerate from the stop bar, which sometimes caused platoons to miss the green band at the site. Reasons for the increases in stops at the US 17 NB site were less apparent, although they may have been influenced by an unsignalized interchange with SR 134 in the middle of the section and a high driveway density, which may have both acted to break up platoons.

Table 8. Change in Number of Stops From Floating Car Data

Jurisdiction	Route	Length (mi)	No. of Signals	Change in Average No. of Stops Over Route (Both Directions)			
				7-9 AM	11 AM-1 PM	4-6 PM	Mean
Fauquier	US 29	9.4	6	*-0.8 (-34.6%)*	***-1.1 (-51.0%)***	0.0 (0%)	-0.6 (-28.5%)
Fairfax	SR 620 (Braddock)	1.6	5	***-0.6 (-9.3%)***[a]	*-0.7 (-30.3%)*	***-2.5 (-40.6%)***	-1.3 (-26.7%)
Frederick	US 11	0.7	6	***+0.4 (+28.3%)***	***+0.3 (+29.0%)***	***-0.1 (-5.8%)***[a]	+0.2 (+17.3%)
Albemarle / City of Charlottesville	US 250	2.0	8	***-3.8 (-63.0%)***	***-2.1 (-54.3%)***	***-3.5 (-67.9%)***	-3.1 (-61.7%)
Frederick / City of Winchester	US 17/50/522	0.9	5	*-0.2 (-14.3%)*	*-0.5 (-28.6%)*	+0.1 (+6.5%)	-0.2 (-12.8%)[a]
Frederick	SR 277	1.4	7	***-1.0 (-34.8%)***	***-0.8 (-32.3%)***	***-1.4 (-43.2%)***	-1.1 (-36.8%)
Frederick / City of Winchester	SR 7	2.3	12	***-1.9 (-43.6%)***	*-1.0 (-27.2%)*	*-1.4 (-31.2%)*	-1.4 (-34.0%)
York	US 17	7.2	19	-1.0 (-7.5%)	***-2.0 (-31.5%)***	***0 (0%)***[b]	-1.0 (-14%)
Augusta / City of Staunton	US 250	1.8	10	***-1.3 (-54.1%)***	***-2.7 (-65.2%)***	***-2.5 (-60.4%)***	-2.2 (-59.9%)
Frederick / City of Winchester	US 50	2.1	8	***-0.7 (-27.1%)***	*-0.9 (-31.0%)*	***-1.3 (-47.6%)***	-0.9 (-35.2%)
Roanoke / City of Roanoke	SR 419 (Electric)	2.0	9	*-0.5 (-16.1%)*	*-0.7 (-9.1%)*	*-1.4 (-35.5%)*	-0.8 (-20.0%)
Campbell / City of Lynchburg	US 29	5.8	11	***-2.0 (-46.0%)***	***-2.0 (-50.5%)***	***-3.0 (-59.0%)***	-2.3 (-51.8%)
York	SR 171 (Victory)	1.1	5	***-2.0 (-61%)***	***-2.0 (-61.5%)***	***-2.0 (-53.5%)***	-2.0 (-59%)

Differences in cells with bold, italics, and underlining were statistically significant for both directions during all time periods. Differences in italics only were statistically significant in only one direction of travel.
[a] Note that stops increased in one direction while declining in the other direction.
[b] NB stops increased, but SB stops decreased, causing performance to cancel out.

Changes in Mean Mainline Speed Based on Floating Car Data

Changes in the end-to-end mainline average speeds using the floating car data are shown in Table 9. Again, *t*-tests with $\alpha = 0.05$ were used to compare changes in average speeds before and after ASCT was installed. Positive values in the table indicate an increase in mean speed at a site following ASCT activation. Values shown in italics were significant in one direction of travel, whereas values shown in italics and bold were significant in both directions. A total of 57 of 78 (73.1%) comparisons were statistically significant.

Of the time periods in which speeds changed significantly, only 6 comparisons (7.7%) showed a significant reduction in speed following ASCT installation. The cases for which speeds became significantly slower were the SB direction on US 11 in Frederick County for all three time periods; US 17/50/522 EB in Winchester during the AM and midday periods; and US 17 NB in York during the PM period. Even though AM peak period speeds declined at Braddock Road, the decrease was not statistically significant because of large variations in travel times during that period. In the case of the US 11 site, decreases in speeds were related to the heavy truck and progression issues noted previously. On US 17/50/522 EB, speeds decreased in the EB direction but increased in the westbound (WB) direction. As a result, it appeared that the ASCT system reallocated the timings to favor the WB direction at the expense of the EB flow, which was the off peak direction during the AM period.

The remaining 51 comparisons (65.4%) that were significant showed increases in speeds. At sites where ASCT produced positive effects, speeds typically increased by 3 to 5 mph, although in some cases increases more than 9 mph were observed.

Pearson correlation coefficients were calculated to determine if there was a correlation between key traffic and geometric features and changes in mean speed. Factors examined included AADT, signal density, density of access points, and number of access points. No significant correlation was found between changes in speed and these factors.

Table 9. Change in Mean Speed From Floating Car Data

Jurisdiction	Route	Length (mi)	No. of Signals	Change in Average Speed Over Route (Both Directions Combined)			
				7-9 AM	11 AM-1 PM	4-6 PM	Mean
Fauquier	US 29	9.4	6	*+2.4 (+4.8%)*	*+1.7 (+3.3%)*	*-1.2 (-2.4%)*	+1.0 (+1.9%)
Fairfax	SR 620 (Braddock)	1.6	5	-1.0 (-4.8%)	*+2.7 (+9.0%)*	*+2.4 (+11.5%)*	+1.4 (+5.2%)
Frederick	US 11	0.7	6	*-3.4 (-11.3%)*	*-3.5 (-12.0%)*	***-0.1 (-0.2%)***[a]	-2.3 (-7.8%)
Albemarle / City of Charlottesville	US 250	2.0	8	***+10.8 (+58.8%)***	***+6.5 (+28.2%)***	***+10.2 (+52.6%)***	+9.2 (+46.5%)
Frederick / City of Winchester	US 17/50/522	0.9	5	***-0.7 (-1.9%)***[1]	***+0.1 (+0.9%)***[1]	*+0.4 (+1.7%)*	-0.1 (-0.4%)[a]
Frederick	SR 277	1.4	7	*+3.6 (+15.1%)*	***+3.3 (+13.3%)***	***+4.4 (+20.3%)***	+3.8 (+16.2%)
Frederick / City of Winchester	SR 7	2.3	12	***+4.5 (+19.3%)***	*+3.7 (+14.9%)*	***+3.9 (+18.2%)***	+4.0 (+17.5%)
York	US 17	7.2	19	+0.2 (+1%)	***+2.3 (+7.5%)***	***-1.0 (-3%)***[a]	+0.48 (+2%)
Augusta / City of Staunton	US 250	1.8	10	***+3.0 (+9.9%)***	***+7.9 (+36.1%)***	***+6.6 (+29.0%)***	+5.8 (+25.0%)
Frederick / City of Winchester	US 50	2.1	8	+2.1 (+6.9%)	*+2.9 (+9.4%)*	*+3.7 (+12.8%)*	+2.9 (+9.7%)
Roanoke / City of Roanoke	SR 419 (Electric)	2.0	9	*+1.5 (+5.9%)*	+4.5 (+20.0%)	+5.4 (+26.3%)	+3.8 (+17.4%)
Campbell / City of Lynchburg	US 29	5.8	11	***+6.0 (+20%)***	***+6.6 (+24%)***	***+6.6 (+27%)***	+6.4 (+24%)
York	SR 171 (Victory)	1.1	5	***+8.7 (+42%)***	***+6.8 (+30.5%)***	***+7.0 (+36.5%)***	+7.5 (+35%)

Differences in cells with bold, italics, and underlining were statistically significant for both directions during all time periods. Differences in italics only were statistically significant for only one direction of travel.
[a] Performance improved in one direction but declined in the other direction, which caused the combined numbers to cancel out.

Changes in Mainline Travel Time From Floating Car Data

Table 10 summarizes the changes in average mainline travel times that were observed at each site using floating car data. Again, *t*-tests with $\alpha = 0.05$ were used to compare changes in average travel time before and after ASCT was installed. Positive values in the table indicate an increase in mean travel times (i.e., performance degraded) at a site following ASCT activation. Values shown in italics were significant in one direction of travel, whereas values shown in italics and bold were significant in both directions. A total of 58 of 78 comparisons (74.4%) were statistically significant.

Table 10. Change in Travel Time From Floating Car Data

Jurisdiction	Route	Length (mi)	No. of Signals	Change in Average Travel Time Over Route (Both Directions Combined)			
				7-9 AM	11 AM-1 PM	4-6 PM	Mean
Fauquier	US 29	9.4	6	*-0:35 (-4.6%)*	*-0:23 (-3.1%)*	*+0:19 (+2.5%)*	-0:13 (-1.7%)
Fairfax	SR 620 (Braddock)	1.6	5	+0:54 (+10.3%)	*-0:29 (-9.1%)*	*-0:48 (-9.7%)*	-0:08 (-1.8%)
Frederick	US 11	0.7	6	*+0:26 (+15.6%)*	*+0:22 (+13.2%)*	***+0:12 (+6.4%)***[b]	+0:20 (+11.7%)
Albemarle / City of Charlottesville	US 250	2.0	8	***-3:27 (-36.6%)***	***-1:35 (-21.7%)***	***-2:52 (-33.4%)***	-2:38 (-30.5%)
Frederick / City of Winchester	US 17/50/522	0.9	5	***-0:05***[1] ***(-1.4%)***	***-0:11***[a] ***(-1.1%)***	*-0:14 (-3.5%)*	-0:10 (-1.4%)[a]
Frederick	SR 277	1.4	7	***-0:40 (-13.1%)***	***-0:38 (-13.0%)***	***-1:13 (-21.4%)***	-0:50 (-15.8%)
Frederick / City of Winchester	SR 7	2.3	12	***-1:10 (-16.1%)***	*-0:48 (-11.8%)*	***-1:13 (-15.4%)***	-1:04 (-14.4%)
York	US 17	7.2	19 (after full deployment)	-0:07 (-0.5%)	***-1:01 (-7%)***	***+0:25***[c] ***(+3%)***	-0:14 (-2%)
Augusta / City of Staunton	US 250	1.8	10	***-0:26 (-9.2%)***	***-1:42 (-26.3%)***	***-1:17 (-20.7%)***	-1:08 (-18.7%)
Frederick / City of Winchester	US 50	2.1	8	-0:19 (-6.5%)	*-0:26 (-9.0%)*	*-0:35 (-11.4%)*	-0:26 (-9.0%)
Roanoke / City of Roanoke	SR 419 (Electric)	2.0	9	*-0:15 (-4.9%)*	*-0:54 (-15.2%)*	*-1:15 (-19.1%)*	-0:48 (-13.0%)
Campbell / City of Lynchburg	US 29	5.8	11	***-1:19 (-16.6%)***	***-1:42 (-19.5%)***	***-2:02 (-21.2%)***	-1:41 (-19.5%)
York	SR 171 (Victory)	1.1	5	***-1:33 (-29.5%)***	***-1:12 (-23.5%)***	***-1:35 (-27%)***	-1:26 (-27%)

Differences in cells with bold, italics, and underlining were statistically significant for both directions during all time periods. Differences in italics only were statistically significant in only one direction of travel.

[a] The EB direction saw consistent degradation in performance, and the WB direction saw consistent improvements in performance. The combined performance canceled out.

[b] The NB direction saw improvements in performance, whereas the SB direction saw a degradation in performance. The combined effect partially canceled out.

[c] The NB direction declined in performance, but the SB direction improved.

Since travel time is the inverse of speed, sometimes the results of the statistical comparisons were slightly different between the two measures. For example, it may be easier to detect statistically significant changes in travel times than speeds when conditions are very congested. A change in speed from 3 mph to 6 mph represents a fairly small change in speed that may not be detected as statistically significant. This would translate into a large travel time change of about 10 min on a 1-mi section of road, which is more likely to be detected as a statistically significant change.

A total of 7 (9.0%) comparisons showed statistically significant increases in travel time. Comparisons where significant increases in travel time occurred included:

- *US 29, Fauquier County.* Travel times increased in the SB direction by 24 sec (+3.2%) during the PM peak, which was statistically significant. This was an approximate 1.5 mph reduction in average speed.

- *US 11, Frederick County.* Travel times increased in the SB direction in all time periods. This was likely caused by the signal progression issues mentioned earlier.

- *US 17/50/522, Frederick County / City of Winchester.* Travel times increased in the EB direction in the AM and midday periods by 15 and 20 sec, respectively. This translated into speed reductions of approximately 4.5 mph. Speeds increased in the WB direction during these two time periods.

- *US 17, York County.* Travel times increased in the NB direction during the PM peak. This mirrors increases in stops and decreases in travel times shown in Tables 8 and 9 for this site.

The remaining 51 comparisons (65.4%) showed statistically significant reductions in travel times. Locations that experienced significant reductions in travel times were typically improved by 10% to 25%.

Side Street Delays

Side street delays were collected at two to four high-volume intersections at each site using the HCM methodology (Transportation Research Board, 2010). In total, side street delays were collected for a total of 40 intersections across the 13 corridors. Data were collected using the same time periods (AM peak, midday, and PM peak) that were used for the floating car data collection. In this case, no statistical tests could be performed since delays were calculated over each period. The change in the average delay per side street approach vehicle is shown in Table 11, with positive numbers indicating increased delays. In the case of the 3 intersections with Braddock Road, queues were so long that it became impossible to collect delays using the HCM method. Instead, queue lengths were measured in terms of either number of cars (if all cars could be viewed simultaneously) or queue length (if queue discharge at the stop line could not be viewed). As a result, average delay changes were determined for 37 intersections × 3 time periods = 111 combinations of time periods and intersections.

Table 11. Average Change in Side Street Delays on Pilot Corridors

Jurisdiction	Route	Intersections Evaluated	Change by Time of Day (sec/veh)			
			7-9 AM	11 AM-1 PM	4-6 PM	Mean
Fauquier	US 29	Lord Fairfax / Bus 17/29 Dumfries/Colonial Broad Run Church / Beverly Mills	+12.4 +15.5 -4.4	+0.7 +8.4 +2.8	+1.5 -8.1 -2.4	+4.9 +5.3 -1.3
Fairfax	SR 620 (Braddock)	SR 123 Sideburn/Mattaponi Roberts	+238.2 ft +3.0 veh -1.0 veh	+0.5 veh -0.6 veh -1.8 veh	-663.9 ft +1.3 veh -3.6 veh	See Note *a*
Frederick	US 11	Welltown/Amoco I-81 NB off ramp Merchant/Snowden	+16.3 +7.7 -23.3	-0.3 -0.8 -23.3	+7.2 +6.7 -9.0	+7.7 +4.5 -18.5
Albemarle / City of Charlottesville	US 250	River Rd / High St I-64 EB ramp	+1.0 +7.2	-10.0 +6.1	+2.3 +7.8	-2.2 +7.0
Frederick / City of Winchester	US 17/50/522	Frontage Rd / Bob Evans I-81 SB off ramp Prince Frederick / Custer	-0.9 +6.2 +6.4	+5.2 +5.8 -1.6	-9.2 -1.3 +4.4	-1.6 +3.6 +3.1
Frederick	SR 277	Aylor I-81 NB off ramp I-81 SB off ramp Warrior	+9.6 +0.2 +5.9 -3.2	+21.1 -1.3 +7.4 +1.8	+12.1 +4.4 +15.1 -11.7	+14.3 +1.1 +9.5 -4.4
Frederick / City of Winchester	SR 7	Fort Collier / Elm I-81 SB off ramp I-81 NB / Valley Mill Gateway	+8.2 -5.8 +2.4 +10.5	+15.6 -11.4 +3.1 +2.3	+15.2 -16.9 +5.8 +13.1	+13.0 -11.4 +3.8 +8.6
York	US 17	Denbigh Lakeside Wolf Trap Coventry	+24.1 +6.6 -3.8 +38.4	+9.1 +15.8 +1.2 +13.8	+52.6 +18.4 -6.3 +21.0	+28.6 +13.6 -3.0 +24.4
Augusta / City of Staunton	US 250	Statler Frontier I-81 SB off ramp	+4.9 +2.1 -0.5	+12.3 +9.3 +6.8	-1.6 +7.6 +4.3	+5.2 +6.3 +3.5
Frederick / City of Winchester	US 50	Round Hill / Retail SR 37 NB off ramp Westside Station / Campus	-1.3 -2.9 +2.7	-1.0 -4.2 +6.5	-6.8 +9.1 +5.1	-3.0 +0.7 +4.7
Roanoke / City of Roanoke	SR 419 (Electric)	Tanglewood/Wendy's Ogden Starkey	+22.1 +4.2 +31.2	+10.4 +1.9 -12.8	+29.8 +8.5 +7.3	+20.7 +4.8 +8.6
Campbell / City of Lynchburg	US 29	Lawyers Old Wards Rd Wards Ferry Rd	+2.4 -42.3 +2.8	+19.5 -30.1 +8.8	+8.9 -27.5 -10.5	+10.3 -33.3 +0.4
York	SR 171 (Victory)	Kiln Creek SR 134	+0.4 +21.2	+16.2 +21.4	+25.1 +27.0	+13.9 +23.2

Negative numbers indicate that ASCT reduced side street delay.
[a] Side street queues at Braddock Road were too long to perform an HCM delay study. Instead, the number of vehicles in the queue or the length of the queue was monitored.

On average, these 111 combinations showed a mean increase in side street delay of 4.7 sec/veh following ASCT activation. In a total of 78 of 111 (70.3%) cases, some increase in delay occurred; in the remaining 33 cases (29.7%), delays were reduced. The distribution of delays is shown in Figure 1. The most common outcome for side street delays was an increase in delay of between 5 and 10 sec/veh. Thus, although ASCT usually improved mainline performance, it often degraded performance on the side streets. Field observations by regional traffic engineering staff indicated that although side street traffic may have been held for longer periods, the corresponding side street green phases were usually long enough to serve all waiting traffic in a single cycle.

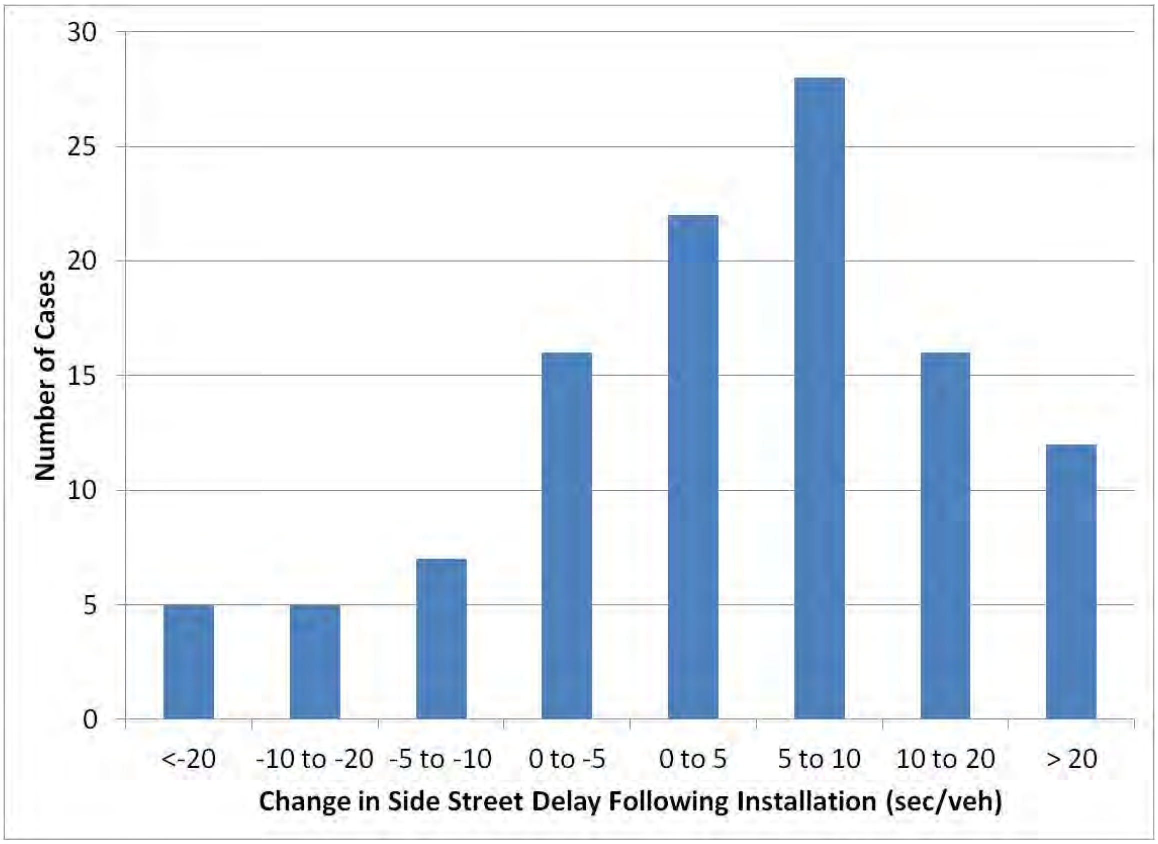

Figure 1. Change in Side Street Delay Following ASCT Activation

Bluetooth Data Analysis

Although the floating car data provide detailed information during the periods when data were collected, the staffing requirements and costs of data collection limit the amount of time when data could be gathered. To overcome this issue, Bluetooth re-identification was used to collect data continuously at several high-volume sites where Bluetooth sample sizes were large enough to make robust estimates of mean performance. These Bluetooth readers operated 24 hr per day during their deployment, enabling the researchers to examine the performance of ASCT during off-peak hours.

As noted in the "Methods," the sample size of Bluetooth probes was checked in each 15-min interval to ensure that sufficient samples were present to estimate mean performance. All available intervals that satisfied the minimum required sample size were then used to determine performance by TOD. The travel times were then estimated for the AM peak (7-11 AM), midday peak (11 AM-4 PM), PM peak (4-7 PM), early evening (7-11 PM), and overnight (11 PM-7 AM). *T*-tests with $\alpha = 0.05$ were conducted to compare travel times with and without ASCT on the mainline road.

Table 12 summarizes the changes in speed at the six sites where robust Bluetooth data were available. Although Bluetooth data were collected at the SR 419 site, the sample sizes were not large enough to generate reliable speed estimates so that site was omitted from the analysis. Generally speaking, data from before ASCT was activated were available for 2 weeks to 1 month. An approximate 1-month period after ASCT was activated was used for comparison. Specific dates used in the analysis are noted in Table 12. Time periods when the *t*-tests did not reveal statistically significant changes in performance at $\alpha = 0.05$ are labeled "NSD."

Table 12. Changes in Mainline Speed Based on Bluetooth Data

Site	Direction	Change in Mean Speed (mph)				
		AM Peak (7-11 AM)	Midday (11 AM-4 PM)	PM Peak (4-7 PM)	Early Evening (7-11 PM)	Overnight (11 PM-7 AM)
US 29, Campbell/ Lynchburg	NB	+2.3	+1.5	+3.5	NSD	NSD
	SB	+3.0	+5.0	+6.9	NSD	NSD
US 17, York	NB	+2.6	+3.8	+4.5	NSD	NSD
	SB	+6.5	+4.5	+4.2	+3.1	NSD
SR 7, Frederick/ Winchester	EB	+4.0	+3.9	+6.8	NSD	NSD
	WB	+4.8	+6.0	+5.7	+4.3	NSD
US 250, Augusta/ Staunton	EB	+8.6	+9.7	+6.2	+5.6	+6.5
	WB	+4.5	+6.7	+4.6	+2.3	NSD
US 17/50/522, Frederick/ Winchester	EB	NSD	NSD	NSD	NSD	NSD
	WB	+5.5	+5.2	+7.7	+2.7	NSD
SR 620 (Braddock Rd), Fairfax	EB	NSD	+1.7	NSD	NSD	NSD
	WB	NSD	-2.0	-2.6	NSD	NSD

NSD = no significant difference.
Dates of data collection were as follows:

- US 29 Lynchburg: ASCT inactive: 2/15/13-3/15/13, ASCT active: 4/1/13-4/30/13.
- US 17 York County: ASCT inactive 5/29/12-6/17/12, ASCT active: 6/20/12-7/20/12.
- SR 7 Winchester: ASCT inactive: 4/11/12-5/11/12, ASCT active: 5/20/12-6/8/12.
- US 250 Staunton: ASCT inactive: 6/15/12-7/9/12, ASCT active: 8/10/12-9/20/12.
- US 17/50/522 Winchester: ASCT inactive: 3/22/12-4/2/12, ASCT active: 5/3/12-6/6/12.
- Braddock Rd: ASCT active: 2/12/12-3/2/12, ASCT inactive: 4/1/12-5/5/12.

The Bluetooth data revealed several trends that were not present in the floating car data:

- With the exception of US 250 EB in Staunton, no sites had significant changes in performance during the overnight period. Thus, ASCT usually did not produce major changes in performance during low-flow periods.

- Bluetooth data revealed different trends on Braddock Road than the floating car data. The Bluetooth data showed declines in performance in the WB direction during the midday and PM peak periods. The Bluetooth data are likely to be a more reliable indicator of average performance since they covered data over a longer period of time than the floating car data. These findings appear to be more consistent with field observations from the Northern Region than the floating car data.

- The US 17/50/522 Bluetooth data showed no significant difference in performance in the EB direction, whereas the floating car data showed a decline in speeds. Again, the Bluetooth data are expected to be a more reliable measure of long-term performance than the floating car data.

- US 17 in York County had stronger positive benefits than were seen in the floating car data. No decline in NB PM peak period travel speed was observed with the Bluetooth data, although it was present in the floating car data. Instead, speeds were found to have increased during this time period. This implies that the floating car data from the NB direction may have been an anomaly.

Given that the Bluetooth data consisted of information across multiple days and contained many more probe vehicles than the floating car data, they were considered to be a more reliable estimator of average performance than floating car data on facilities where it was available. With the exception of US 17/50/522 EB and Braddock Road, the Bluetooth data showed that ASCT improved performance on the mainline during daytime periods. Increases in speed during the AM peak, midday, and PM peak periods on SR 7, US 17, US 29, and US 250 averaged a 5.0 mph increase.

Travel Time Reliability Analysis Using INRIX Data

Previous research has often suggested that adaptive traffic signals are most beneficial when traffic volumes are variable, but long-term impacts on travel time reliability have not been documented. A key challenge in examining reliability, however, is that a long time series of data is needed to get accurate measurements of the shape of the typical travel time distribution. Since before data were often limited in duration for the Bluetooth data, INRIX data were used to assess reliability. Although the absolute accuracy of the INRIX data remains a question, as noted earlier, it was expected that they would be useful for examining relative changes in reliability. In this case, a longer before period was needed to develop more reliable estimates of the 95th percentile travel time by TOD.

Table 13 shows the change in 95th percentile travel times by day of week and TOD across all sites with INRIX data. All changes shown in the table were determined to be statistically significant using a *t*-test with $\alpha = 0.05$. On average, the largest reductions in 95th percentile travel time occurred during the midday and afternoon periods on weekdays, with smaller impacts during the weekday AM peak and on the weekends. Overnight 95th percentile travel times changed by a relatively small amount, although the amount was still statistically significant. Thus, it does appear that ASCT was able to reduce the severity of the worst days of congestion, although the differences were relatively modest. These results are consistent with

Table 13. Changes in 95th Percentile Travel Time After ASCT Installation (Average Across All Sites)

Day of Week	Morning (6-10 AM)	Midday (10 AM-3 PM)	Afternoon (3-7 PM)	Night (7 PM-6 AM)	Average
Monday	-3.8%	-5.6%	-7.3%	-2.0%	-5.0%
Tuesday-Thursday	-4.0%	-5.7%	-6.4%	-2.4%	-4.9%
Friday	-3.7%	-7.3%	-8.4%	-1.8%	-5.8%
Weekends	-2.9%	-4.2%	-1.4%	-0.6%	-2.3%
Average	-3.6%	-5.9%	-6.2%	-1.7%	-4.6%

other work that hypothesized that adaptive signals work best when traffic demand is highly variable (Hutton et al., 2010; Shetler, 2013).

The buffer index was also examined as another way of representing reliability. Table 14 shows the average changes in buffer index across the six sites where INRIX data were available. Generally speaking, the buffer index improved across the midday, afternoon, and overnight periods during weekdays. Changes in buffer index were more modest during the morning peak period and were mixed on weekends. On average, 15% to 25% improvements in reliability were observed during weekday midday and PM peak periods. Although percentage changes in reliability were large, the magnitude of these changes was often relatively small. Since changes in buffer index are relatively small, this implies that changes in 95th percentile travel time are often relatively proportional to changes in average travel time at the site.

The Pearson correlation coefficient was calculated to determine if the travel time reliability results were correlated with site characteristics. Travel time reliability improvements for all time periods (4 days of the week × 4 times of the day) were tested for correlation with various site-specific factors, including AADT, signal density, density of access points, and number of access points. The only significant correlation that was found was that reliability was inversely correlated with signal density during nighttime periods at a 95% confidence level. The Pearson correlation coefficient for signal density was -0.59. No significant correlation was found for all other site-specific factors.

Table 14. Average Buffer Index Values (Average Across All Sites)

Day of Week	Time Period	Morning (6-10 AM)	Midday (10 AM-3 PM)	Afternoon (3-7 PM)	Night (7 PM-6 AM)	Average
Monday	Before	0.12	0.12	0.15	0.08	0.12
	After	0.11	0.10	0.11	0.07	0.10
	Change	-0.01 (-8.3%)	-0.02 (-16.7%)	-0.04 (-26.7%)	-0.01 (-12.5%)	-0.02 (-16.7%)
Tuesday-Thursday	Before	0.11	0.12	0.15	0.09	0.12
	After	0.11	0.10	0.11	0.08	0.10
	Change	0.0	-0.02 (-16.7%)	-0.04 (-26.7%)	-0.01 (-11.1%)	-0.02 (-16.7%)
Friday	Before	0.11	0.14	0.16	0.09	0.13
	After	0.10	0.11	0.11	0.08	0.10
	Change	-0.01 (-9.1%)	-0.03 (-21.4%)	-0.05 (-31.3%)	-0.01 (-11.1%)	-0.03 (-23.1%)
Weekends	Before	0.08	0.09	0.07	0.07	0.08
	After	0.07	0.08	0.09	0.08	0.08
	Change	-0.01 (-12.5%)	-0.01 (-11.1%)	+0.02 (+28.6%)	+0.01 (+14.3%)	0.0
Average	Before	0.10	0.12	0.13	0.08	0.11
	After	0.10	0.10	0.10	0.08	0.10
	Change	0.0	-0.02 (-16.7%)	-0.03 (-23.1%)	0.0	-0.01 (-9.1%)

Given that the data quality of the INRIX data has not been firmly established on the arterial system, these results should be viewed as being representative of relative changes in performance. Generally speaking, the INRIX data indicate that the ASCT system could produce modest improvements in reliability on the corridor. Further validation of the accuracy of the arterial data would need to be performed before an absolute impact could be ascertained.

Safety Analysis

Table 15 shows the descriptive statistics for the crash data analyzed in this research. There was a total of 1,747 crashes (including 626 FI crashes) during the before period and 393 crashes (including 150 FI crashes) during the after period. The proportion of FI crashes increased slightly from 35.8% in the before period to 38.2% in the after period. The average AADT for both major and minor approaches were similar in the before and after periods.

Table 15. Summary of Crash and Volume Characteristics of Sites Used in Crash Analysis

Time Period	Variable	Annual Mean	Annual Minimum	Annual Maximum	Standard Deviation	Sum Over Period
Before ASCT Installation	Total crashes	6.35	1	25.6	4.89	1747
	FI crashes	2.66	0	7.2	1.71	626
	AADT (major)	24306	6961	50329	12525	6684039
	AADT (minor)	5046	386	20067	4529	1387656
After ASCT Installation	Total crashes	5.95	0	15	3.78	393
	FI crashes	2.27	0	10	2.15	150
	AADT (major)	24470	6667	49384	12640	1862303
	AADT (minor)	4944	387	19010	4361	360057

AADT = average annual daily traffic.

Empirical Bayes Analysis and Results

The EB analysis was conducted using the crash data from the 47 intersections for which AADT data were available. The results are shown in Table 16.

Table 16 shows that installing ASCT at an urban signalized intersection can have a statistically significant effect on reducing total crashes at the 95% confidence level. The CMF was 0.83 with a standard error of 0.05. ASCT installation was not found to have a statistically significant effect on FI crashes. The non-significant FI CMF seems plausible since reductions in stops along the corridor would likely have a greater impact on low-speed crashes.

The EB analysis was also conducted separately for four-leg and three-leg intersections to determine if there were differences in performance by intersection configuration.

Table 16. Crash Modification Factor (CMF) Results and Standard Error

Measure	Total Crashes	FI Crashes
CMF	0.83	0.92
Standard error	0.05	0.08
Safety effectiveness (%)	17.6	11.0
Safety effectiveness / σ	3.70	1.01

FI = fatality plus injury.

Table 17 shows that only the CMF for total crashes at four-legged intersections was significant at the 95% level. These results may be influenced by the smaller number of three-legged intersections (9 of 47) in the data set.

Table 17. Crash Modification Factor (CMF) Results for Three-Legged and Four-Legged Intersections

No. of Legs	Crash Severity	CMF	Standard Error
4	Total crashes	0.79**	0.05
	FI crashes	0.92	0.09
3	Total crashes	0.996	0.13
	FI crashes	0.87	0.19

** indicates significance at the 95% level; FI = fatal plus injury.

Changes in Crash Type Proportions

Although the previous analysis showed that ASCT was able to reduce total crashes, it did not identify whether certain crash types were disproportionately affected by ASCT. It was hypothesized that if stops were reduced at a site, rear-end crashes might see larger declines than other crash types.

Table 18 shows the proportions of each crash type before and after ASCT installation. As may be seen, the distribution of crash types did not change much from the before to the after period. Contrary to expectations, the aggregate proportion of rear-end crashes actually increased slightly following ASCT activation. In order to confirm these results, the shift in proportions of rear-end, angle, and sideswipe crashes was examined using methods recommended by the HSM (AASHTO, 2010). As shown in Table 19, the results indicated no significant changes in the proportions of all three crash types. (Note that the average shift in proportions in Table 19 is calculated by averaging the shift at each site, which is different from the aggregate shift value that can be calculated from Table 18.)

There are several possible explanations as to why a proportionate decrease in rear-end crashes was not observed. As an example, the ASCT system evaluated operates in an acyclic manner, meaning that phases could be skipped or served multiple times per cycle. This behavior may offset potential rear-end crash decreases created through fewer mainline stops. As another example, if drivers are less likely to stop along a corridor, it is possible that they may be less attentive and more likely to make an error during the times when they do need to stop.

Table 18. Crash Type Distribution

Crash Type	Total Crash Before	FI Crash Before	Total Crash After	FI Crash After
Rear-end	896 (51.29%)	319 (50.96%)	226(57.51%)	82 (54.67%)
Angle	538 (30.80%)	202 (32.27%)	110 (27.99%)	49 (32.67%)
Sideswipe same direction	134 (7.67%)	26 (4.15%)	26 (6.62%)	5 (3.33%)
Sideswipe opposite direction	13 (0.74%)	7 (1.12%)	3 (0.76%)	2 (1.33%)
Non-collision	14 (0.80%)	9 (1.44%)	3 (0.76%)	2 (1.33%)
Other	152 (8.70%)	63 (10.06%)	24 (6.11%)	10 (6.67%)
Sum	1747 (100%)	626 (100%)	393 (100%)	150 (100%)

FI = fatal plus injury.

Table 19. Statistical Tests of Proportion Shift for Major Crash Types

Crash Type	Average Shift	T Statistic	$z_{\alpha/2}$ ($\alpha = 0.05$)	$z_{\alpha/2}$ ($\alpha = 0.1$)
Rear-end (Total)	0.0863	0.029	1.96	1.645
Rear-end (FI)	0.0099	0.0152	1.96	1.645
Angle (Total)	-0.0576	-0.0116	1.96	1.645
Angle (FI)	0.0310	0.0105	1.96	1.645
Sideswipe same direction (Total)	0.0004	-0.0039	1.96	1.645
Sideswipe same direction (FI)	-0.0119	0.0216	1.96	1.645
Sideswipe opposite direction (Total)	0.0092	0.0355	1.96	1.645
Sideswipe opposite direction (FI)	0.0058	0.0470	1.96	1.645

FI = fatal plus injury.

Additional investigation into crash types would appear to be warranted as more data become available. Based on the available data, it appears that no statistically significant changes in crash type proportions occurred.

Safety Effects by AADT Level

ASCT is typically deployed to improve mobility at sites where traffic patterns are unpredictable and relatively congested. Given these attributes, it was hypothesized that ASCT could have varying effects by AADT. The average of the major road AADT across the before and after periods was used to create two categories: low volume (6900 < AADT < 30000, 28 sites) and high volume (30000 < AADT < 50200, 27 sites). As shown in Table 20, the odds ratios are not significant at the 90% level at low-volume sites for both total and FI crashes, whereas at high-volume sites the odds ratios are significant at the 95% level for total crashes. This result again implies that higher volume sites are more likely to have benefits from ASCT installation.

Table 20. Odds Ratio by AADT Level

AADT	Total Crashes		Fatal Plus Injury Crashes	
	Odds Ratio	Standard Error	Odds Ratio	Standard Error
6900 < AADT < 30000	0.95	0.08	0.99	0.13
30000 < AADT < 50200	0.72**	0.06	0.85	0.11

AADT = average annual daily traffic; ** significant at the 95% level.

Safety Effects by Corridor and Operational Change

Given that ASCT was installed at multiple intersections along different corridors, it is possible that the safety effects at intersections may not be truly independent of one another within a corridor. As a result, performance along each corridor was examined to determine if there were any consistent trends in safety effect relative to operational changes. Intersections along each corridor were re-analyzed to determine a corridor-specific EB estimate of the odds ratio. Figures 2 and 3 shows these results, with the error bars indicating a 90th percentile confidence interval. The limited number of sites on a by-corridor basis has a strong influence on the width of these confidence intervals, often creating significant statistical uncertainty on a site-by-site basis. Because of this, only four of the corridors evaluated had a total crash odds ratio that was significantly different from 1.0, indicating no ATSC effect on safety. As a result, although it appears that performance differed among corridors, the small sample size in each corridor makes it difficult to detect statistically significant differences in performance. Figure 2 shows the results for total crashes, and Figure 3 shows the results for FI crashes.

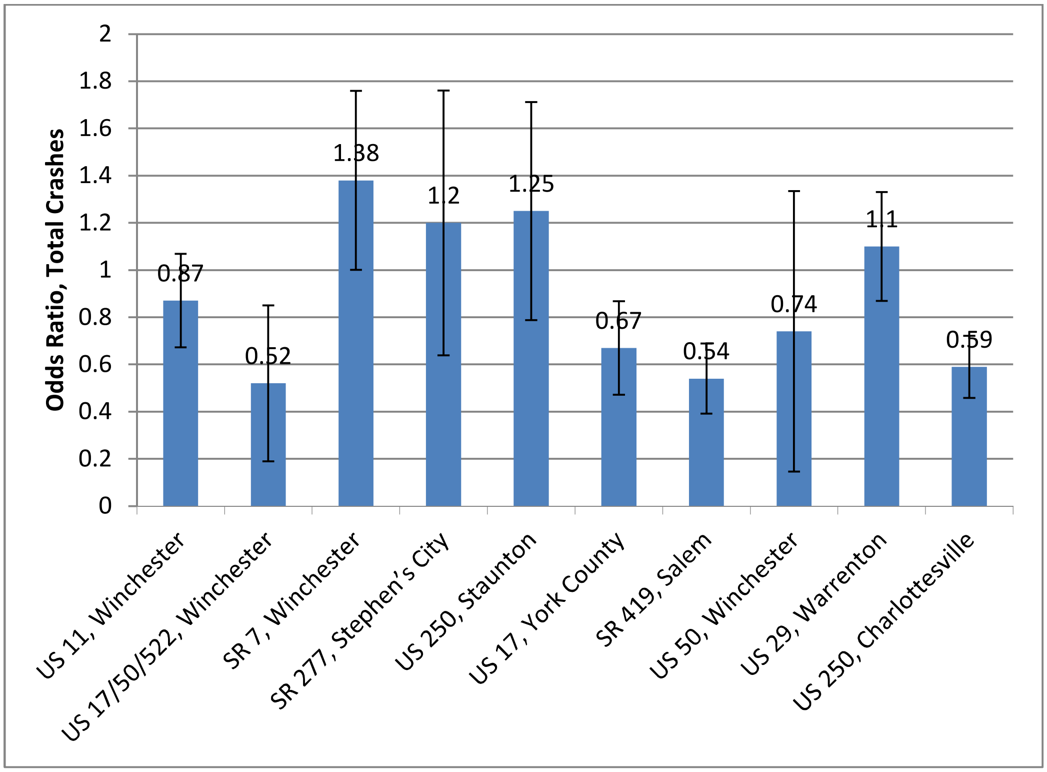

Figure 2. Corridor Odds Ratios for Total Crashes

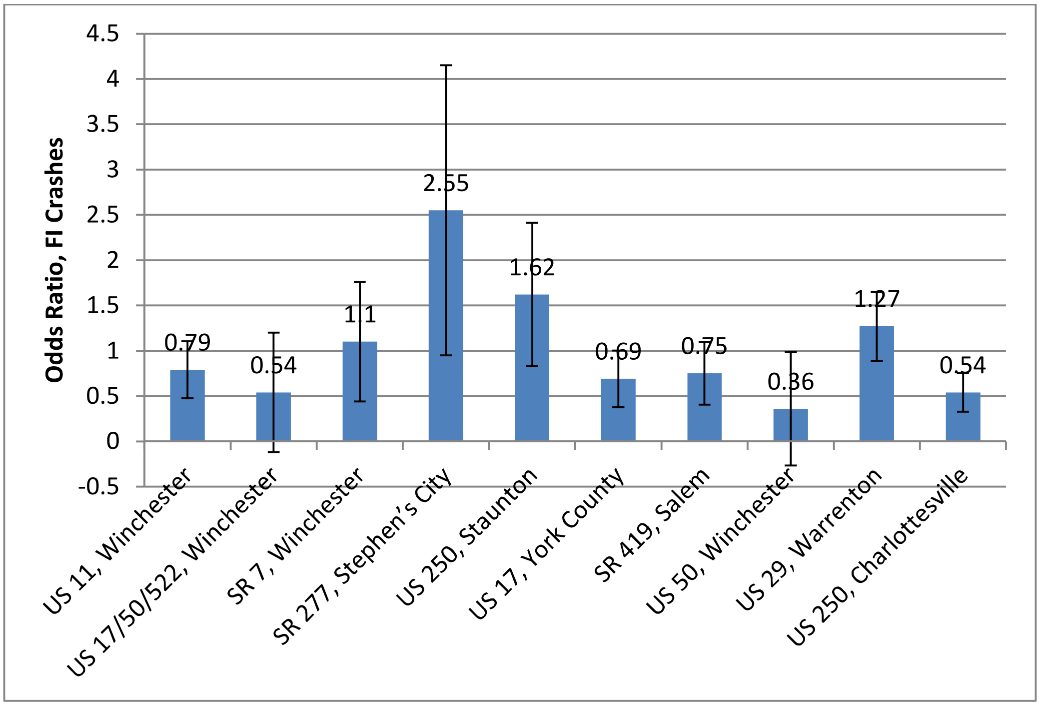

Figure 3. Corridor Odds Ratios for Fatal Plus Injury Crashes

An examination of Figures 2 and 3 reveals that there are no obvious correlations between the site odds ratios and the observed changes in operational performance shown earlier. Correlation coefficients were calculated for the odds ratios and the changes in stops and floating car speed, since floating car data were the only mainline operational assessment available across all sites. Correlations were below 0.2 in all cases, indicating that there was not a direct link between observed safety impact and changes in stops or speeds. Given that rear-end crashes were not disproportionately affected by ASCT, this lack of correlation between mainline operational changes and safety is perhaps not unexpected.

This lack of correlation could be attributable to several causes. First, the operational data presented were focused on the mainline, so it would not capture changes in side street delays. Second, although some sites had data from Bluetooth and private sector probe data providers, the limited floating car data set was the only information consistently available across all sites. Thus, this limited floating car data may not be representative of longer term performance.

Benefit/Cost Analysis

A B/C ratio was calculated for each site where ASCT was deployed to assess the overall net benefit of the system. Table 21 summarizes the results of the B/C analysis. When interpreting the data, it is important to be aware of several of the key assumptions that were discussed earlier in the "Methods":

- Positive user operational benefits indicate that conditions improved with ASCT, and negative benefits indicate that conditions got worse.

- Mainline travel time benefits were computed using either Bluetooth data or GPS floating car data, with Bluetooth data being used if they were available. The Bluetooth data were available 24/7, and benefits were calculated over all available data. The floating car data were available between 7-9 AM, 11 AM-1 PM, and 4-6 PM. That data were used to estimate benefits for those time periods for weekdays only, and benefits/disbenefits were assumed to be 0 during other periods. Thus, operational impacts shown in Table 21 are likely to be conservative for floating car data. Only statistically significant changes in travel times were included in the benefits analysis.

- Side street delays were available from 7-9 AM, 11 AM-1 PM, and 4-6 PM for between two and four intersections per corridor. The side street travel time benefit is the direct user impact for the intersections for which data were collected for those time periods only. Delay changes were assumed to be equal to 0 for other time periods that were not covered by the data.

- Extrapolated side street costs assume that the average intersection impacts on a corridor occurred at all intersections on the subject corridor. Again, this accounts for only the AM, midday, and PM periods for weekdays.

Table 21. Benefit/Cost (B/C) Analysis of Pilot Sites

Site	Annual Mainline Travel Time Benefit	Annual Side Street Travel Time Benefit	Annual Extrapolated Side Street Benefit	Initial System Cost	Annual B/C for Mainline Only	Annual B/C for Mainline + Side Streets Directly Collected	Annual B/C for Mainline + Side Streets Extrapolated to All Intersections
Sites With 24/7 Bluetooth Data on Mainline							
US 17/50/522 (Frederick/Winchester)	$1,178,950	-$16,665	-$27,775	$294,479	4.00	3.95	3.91
US 250 (Augusta/ Staunton)	$3,164,355	-$79,061	-$263,538	$396,089	7.99	7.79	7.32
SR 7 (Frederick/Winchester)	$4,309,017	-$74,684	-$224,053	$495,304	8.70	8.55	8.25
US 29 (Campbell/Lynchburg)	$9,278,173	$245,307	$899,458	$437,415	21.21	21.77	23.27
SR 620 (Braddock Rd, Fairfax)	-$1,455,248	No delay data	No delay data	$303,940	-4.79	n/a	n/a
Sites With Weekday AM, Midday, and PM Floating Car Data							
US 29 (Fauquier)	$148,511	-$37,670	-$75,346	$259,006	0.57	0.43	0.28
US 11 (Frederick)	-$917,691	-$35,967	-$71,936	$241,161	-3.81	-3.95	-4.10
US 250 (Albemarle/Charlottesville)	$8,602,677	-$11,888	-$47,552	$398,518	21.59	21.56	21.47
Route 277 (Frederick)	$2,415,378	-$63,556	-$111,217	$278,529	8.67	8.44	8.27
Route 419 (Roanoke / City of Roanoke)	$2,136,373	-$134,213	-$402,640	$515,552	4.14	3.88	3.36
US 50 (Frederick/Winchester)	$587,451	-$11,455	-$30,545	$193,864	3.03	2.97	2.87
US 17 and SR 171 (Victory Blvd), US 17 Has Bluetooth Data and SR 171 Has Floating Car Data							
US 17 (York)	$9,746,810	-$427,011	-$2,028,302	$1,015,829	13.41	12.50	10.18
SR 171 (Victory, York)	$3,871,443	-$497,709	-$1,244,273				
Total	**$43,066,198**	**-$1,144,570**	**-$3,627,713**	**$4,829,686**	**8.92**	**8.68**	**8.17**

- No side street delays could be calculated for Braddock Road since side street delays could not be consistently collected. Thus, negative impacts at Braddock Road are likely greater than documented.

- Net maintenance costs for the system are not known and are not included. Implications of the lack of maintenance data are discussed in more detail later.

- System costs for US 17 in York County also include costs for Victory Boulevard since those two routes intersect. As a result, only a combined B/C analysis is presented for those two sites.

- Safety benefits of the system are not broken out by site because of the small sample sizes on a per-site basis and the difficulty in determining statistical significance on a corridor basis. Instead, an aggregate benefit was computed across all intersections that were studied. Again, the research examined only intersections for which minor road AADT was available, and segment crashes were not examined. Thus, safety benefits are not included in B/C calculations.

The B/C evaluation of the pilot tests showed that ASCT generally produced a net benefit, with an average B/C ratio based on 1 year of data exceeding 8.0. Although maintenance costs were not included, it is likely that the system would still produce a net benefit given the magnitude of the benefits that were calculated using available data. Two sites were determined to have negative B/C ratios: SR 620 (Braddock Road) and US 11 (Frederick). Only one other site had a 1-year B/C ratio of less than 1.0, i.e., US 29 in Fauquier. Further discussion of these three sites may help explain why ASCT installations at these sites did not produce benefits.

In the case of both Braddock Road and US 11, mainline travel times increased following ASCT installation. Braddock Road operated substantially over capacity during both the AM and PM peak periods. These problems were exacerbated by a high-volume cross street (SR 123) at the east end of the corridor. A further issue on this corridor was that travel patterns of people accessing George Mason University were also conflicting with high-volume PM peak flows in the WB direction. Since the facility was over capacity on multiple approaches, additional optimization during the peak periods did not improve operations over the TOD system. The increased delays on the mainline coupled with perceived negative impacts on the side streets resulted in the Northern Region removing the ASCT and reverting to TOD control.

For US 11, mainline travel times were influenced by the presence of interchanges with I-81 and SR 37 at either end of the corridor and relatively large truck volumes. The ASCT system was coordinated with the I-81 ramp movements, which served to degrade overall mainline travel times and increase stops. This increase in stops, combined with the relatively large number of large trucks, created additional travel time increases on the corridor. As a result, unusual patterns of flows from side streets and large truck volumes could degrade performance.

The benefits for US 29 in Fauquier County were not as large as for other sites, which could likely be attributed to several causes. First, this site had the largest average signal spacing of all of the pilot sites, an average of 1.57 mi between signals. Previous research has shown that it is difficult to maintain platoons of traffic between signals spaced too far apart, thereby losing some of the effectiveness of the ASCT system (Institute of Traffic Engineers, 1999). The issue of platoon dispersion was exacerbated at this site by the presence of two unsignalized grade-separated interchanges at the southern end of the site that injected additional, unmonitored traffic into the system. Second, the site operated relatively well on the mainline prior to ASCT installation. In this case, US 29 had a mean travel speed of between 47 and 52 mph in the before period on a road with posted speeds between 45 and 55 mph. As a result, there was very limited opportunity for ASCT to increase speeds further at the site. These results indicate that benefits may be limited if the site already operates near the posted speed limit, has unsignalized access points with high traffic volumes, wide signal spacings, or other factors that could cause platoons to disperse between intersections. Benefits of ASCT at this site may accrue over a longer period through reduced need for signal timing, but significant, immediate benefits were not observed.

The aggregate safety benefits of the ASCT deployment can be accounted for by monetizing the crash reductions at the intersections that were studied. Since site-specific findings were often not significant because of the limited amount of after data at each site, only an aggregate assessment across the studies sites is provided. As shown in Table 16, the EB analysis found that the CMF for total crashes was a statistically significant 0.83, whereas there was no statistically significant reduction of FI crashes.

There was 1,747 total crashes at the 47 test sites used in the analysis during the 5-year before period, resulting in an average of 7.43 crashes per intersection per year. If the CMF of 0.83 is applied, it can be broadly estimated that there would have been an average of 6.17 crashes per intersection per year if ASCT had been installed. Since no statistically significant reduction in FI crashes was found, it can be assumed that this reduction of 1.26 crashes/intersection/year comprised only property damage crashes. Assuming the VDOT Highway Safety Improvement Program costs of $9,000 per property damage crash (VDOT, 2012), this would equal an average benefit of $11,340 in crashes prevented per intersection per year. This is only a rough planning estimate, and this would need to be refined for site-specific conditions in future deployments.

Overall Site Summary

Since ASCT performance for each site was evaluated using multiple metrics, it is useful to try to summarize the major findings by site. For the sake of such a summary, each performance measure was rated using five levels ranging from a large decline in performance to a large improvement in performance. Table 22 shows the definitions of each of the five levels for each performance measure and assigns a symbol to represent the average performance at the site. Table 23 uses these symbols to try to show concisely how each site performed across performance measures. In addition to the factors shown in Table 23, the study found that ASCT produced around a 5% reduction in corridor 95th percentile travel times and a 17% reduction in property damage only crashes at intersections.

In general, the findings of this study corroborate the results in earlier evaluations of InSync. Performance generally improved along the mainline route, but delays increased on side

Table 22. Definitions of Symbols Used in Table 23

Factor	Symbol and Meaning				
	⇩ (Large decline in performance)	⬃ (Small decline in performance)	⇔ (Marginal effect)	⬀ (Small improvement in performance)	⇧ (Large Improvement in performance)
Mean No. of Stops (Floating Car)	Stops increase > 20%	Stops increase by 10% to 20%	Stops change by +10% to -10%	Stops decrease by 10% to 20%	Stops decrease by > 20%
Mean Speed (Floating Car)	Speeds decrease > 20%	Speeds decrease by 10% to 20%	Speeds change by +10% to -10%	Speeds increase by 10% to 20%	Speeds increase by > 20%
Mean Travel Time (Floating Car)	Travel time increases > 20%	Travel time increases by 10% to 20%	Travel time changes by +10% to -10%	Travel time reduced by 10% to 20%	Travel time reduced by > 20%
Median Side Street Delay	Delays increase > 15 sec/veh	Delays increase by 5% to 15 sec/veh	Delays change by +5 to -5 sec/veh	Delays reduced by 5 to 15 sec/veh	Delays reduced by > 15 sec/veh
Mean Speed (Bluetooth)	Speeds decrease > 20%	Speeds decrease by 10% to 20%	Speeds change by +10 to -10%	Speeds increase by 10% to 20%	Speeds increase by > 20%
B/C Ratio	B/C < -1.0	B/C between 0 and -1.0	B/C between 0 and 1.0	B/C between 1.0 and 5.0	B/C > 5.0

streets. Table 23 shows that the ASCT system appeared to create a net benefit at 10 of the 13 pilot sites where it was installed. Some important trends in the data included the following:

- The floating car data showed that average mainline performance usually improved in several areas.
  - The average number of stops on the mainline declined at 12 of 13 sites, with 9 of 13 sites experiencing declines of more than 20%.
  - ASCT had a neutral to very positive effect on mean speed at every site. Improvements were less dramatic than for number of stops, but 7 of 13 sites had mean speed increases of at least 10%. Trends were similar for travel time.
- ASCT had a neutral to very negative effect on median side street delay based on the locations where data were collected. A neutral effect on median delay was observed at 6 of 13 sites. Median delays increased by more than 15 sec/veh at one site.
- Mean Bluetooth speeds showed that ASCT had a neutral to very positive effect at the sites with available data. The Bluetooth data often did not show as large of an impact as the floating car data, but it often quantified additional benefits beyond the time periods when floating car data were collected.
- Overall, the B/C analysis that accounted for the initial installation cost, mainline travel time improvements, and side street delays found that the system provided a clear net benefit at 10 of 13 sites and a marginal benefit at 1 additional site. ATSC did not provide a benefit for 2 sites.

Table 23. Site Performance Summary

Location	Mean # of Stops (Floating Car)	Mean Speed (Floating Car)	Mean Travel Time (Floating Car)	Median Side Street Delay	Mean Speed (Bluetooth)	B/C Ratio
US 29, Fauquier	⇧	⇔	⇔	⇔	n/a	⇔
SR 620 (Braddock), Fairfax	⇧	⇔	⇔	n/a	⇔	⇩
US 11, Frederick	⬃	⇔	⬃	⇔	n/a	⇩
US 250, Albemarle/ Charlottesville	⇧	⇧	⇧	⇔	n/a	⇧
US 17/50/522, Frederick/ Winchester	⬀	⇔	⇔	⇔	⇔	⬀
SR 277, Frederick	⇧	⬀	⬀	⬃	n/a	⇧
SR 7, Frederick/ Winchester	⇧	⬀	⬀	⬃	⬀	⇧
US 250, Augusta/ Staunton	⇧	⇧	⬀	⬃	⇧	⇧
US 50, Frederick/ Winchester	⇧	⇔	⇔	⇔	n/a	⬀
SR 419 (Electric), Roanoke/City of Roanoke	⬀	⬀	⬀	⬃	n/a	⬀
US 29, Campbell/ Lynchburg	⇧	⇧	⬀	⇔	⬀	⇧
US 17, York	⬀	⇔	⇔	⇩	⬀	⇧
SR 171 (Victory), York	⇧	⇧	⇧	⇩	n/a	

n/a = Not applicable, since no Bluetooth data were available at these sites.

Considerations for Future ASCT Deployment

It was initially expected that quantitative guidelines could be developed to identify site traffic/geometric conditions that would benefit the most from ASCT. Unfortunately, correlation analysis between operational measures and features such as AADT, signal density, and access point spacing did not reveal statistically strong correlations. As a result, the guidelines presented here are more qualitative in nature. Instead of firm guidelines, issues that should be considered before deploying future systems are reviewed. In some cases, these considerations were derived from issues encountered during the system deployment as opposed to evaluation of the metrics discussed earlier. Information identified from regional traffic engineering staff and VDOT's TED was incorporated into this list of considerations. These considerations can be generally categorized into traffic considerations, site considerations, and institutional considerations. Although these considerations are expected to be broadly applicable across ASCT vendors, they were developed using data only from the InSync pilot deployment.

Traffic Considerations

- *ASCT is most beneficial at locations where some congestion is present but the corridor is not oversaturated for extended periods of the day.* Ten of 13 pilot sites had improvements in mainline flow and net overall benefits. All of these sites had some level of congestion and delay, although multiple cycle failures were not observed.

- *ASCT is not likely to produce significant benefits when a road is substantially over capacity, especially when all approaches at major, high-volume intersections are oversaturated.* If demand volumes far exceed available capacity, additional optimization of the system is unlikely to produce benefits. Thus, ASCT should not be installed primarily to deal with peak period congestion where all approaches are oversaturated.

- *If the mainline route is already operating well, ASCT is unlikely to create substantial further improvements in operations.* ASCT may provide benefits in terms of safety or reduced need to re-time signals, but mainline travel times are unlikely to improve by a substantial margin. Although ASCT is unlikely to create negative impacts, sites that are already functioning well may not represent the most cost-effective location to deploy the system.

- *Delays are likely to increase on side street approaches, so care should be taken if existing side street delays are already a concern.* On average, the pilot test found that side street delays often increase by 5 to 10 sec/veh. If side street delays are already a source of complaints, ASCT could exacerbate concerns.

- *ASCT is likely to be most effective at sites with variable traffic demands attributable to seasonal variations, school schedules, incidents, special events, etc.* If demand volumes are consistent, TOD plans are likely to operate acceptably. The pilot test results revealed that travel time reliability metrics often improved at the sites where ASCT was deployed.

- *ASCT may not be as effective on routes with higher truck volumes.* Although this is based on limited data, there were issues with mainline traffic flow at the US 11 site because of the longer times for trucks to accelerate from a stop versus passenger cars. The impact of truck performance should be considered especially when roadway grades may influence truck accelerations.

Site Considerations

- *Long signal spacings will reduce the effectiveness of ASCT.* One of the less effective pilot deployments occurred at a site with average signal spacings of more than 1.5 mi. When signal spacings are long, platoons will disperse while traveling between intersections. The platoon dispersion will limit the ability of ASCT to develop effective green tunnels along a corridor.

- *High-volume unsignalized access points on the corridor may limit the effectiveness of ASCT.* Several pilot sites (such as US 29 in Warrenton) had unsignalized interchanges located within the test section. These interchanges were sometimes the source of large volumes of traffic that were not monitored by the ASCT system. Since these inputs to the network were not visible to the ASCT system, the system did not implicitly account for them in the construction of the green tunnels. As a result, care should be taken when deploying ASCT along corridors with unsignalized intersections or driveways with large volumes.

- *InSync offers a way to coordinate signals on corridors that run different controller platforms or reside in different jurisdictions.* Since the InSync processor is installed on top of existing controller hardware, it can be used explicitly to coordinate signals running different signal controllers. This is particularly beneficial when signals on a corridor are operated by VDOT and a city since InSync can explicitly perform cross-jurisdictional coordination. Five of the 13 sites in the pilot program operated across jurisdictional boundaries, which allowed true coordination to occur across city lines. Some of the benefits documented for those corridors may have resulted from providing true coordination across jurisdictional boundaries rather than clock-based TOD coordination.

- *Communications must be reliable for the system to function properly.* Communications between intersections must be reliable for the system to function as intended. Ideally, communications between intersections would be handled using fiber optic cable. In more rural locations, wireless communications were used to communicate between intersections, but this sometimes created issues. In at least one pilot site, wireless communications had to undergo significant troubleshooting multiple times to ensure that there were no significant lapses in communications. A thorough analysis of the communications design should be performed when wireless radios will be used to connect widely spaced signals or traffic signals where the topography may limit line of sight communications.

Institutional Considerations

- *Ongoing maintenance requirements for the ASCT system may be greater than those of traditional TOD systems, but several maintenance benefits are also possible.* Several regions noted that there were increased calls to the ASCT corridors to deal with malfunctioning detectors, processors, or communications equipment. Since ASCT relies on the presence of well-functioning detection, regions should plan on regular maintenance to ensure that detection and processors are functioning properly. Although ongoing maintenance may be more demanding than for TOD systems, some benefit will also be achieved since signals will not have to be re-timed regularly. Likewise, the ASCT system offers the ability to monitor and control sites remotely. This could allow operators to diagnose problems and re-set certain hardware without dispatching maintenance crews. This improved monitoring and control ability could eliminate the need to respond in the field to some trouble calls and also improve the productivity of maintenance crews by remotely diagnosing issues.

- *If ASCT has not been previously installed in the area, VDOT should reach out to local law enforcement and the public to educate them on the system operation.* Since InSync does not have a fixed cycle length or phase order, it is important that law enforcement officials and the public understand that the system is not malfunctioning if it skips a phase or serves a phase twice.

CONCLUSIONS

- *Conclusions are based on testing of the InSync system.* Although the major findings may be applicable across ASCT vendors, the magnitudes of changes may vary depending on how a specific ASCT system is operated.

- *ASCT generally improves mainline operations if the corridor (1) is not over capacity (2) does not have traffic or geometric characteristics that impair progressive flow, or (3) does not already operate at a good level of service.* There are no benefits during oversaturated conditions since green time cannot be reallocated effectively. Likewise, high-volume unsignalized access points, long signal spacings, or high truck volumes all seem to be related to reduced effectiveness. In addition, ASCT does not create measurable improvements in performance on corridors that already function well. As a result, ASCT should be considered when some congestion is present at a location at certain times of day, but the corridor should not routinely have multiple cycle failures.

- *Side street delays generally increase when ASCT is deployed, although there is usually a net reduction in overall corridor delay.* Generally speaking, improvements in mainline performance come at the cost of increased side street delay. When these changes are aggregated together, it is estimated that the system provides a net benefit when the three factors mentioned previously (i.e., corridor was not over capacity, did not have traffic or geometric characteristics that impaired progressive flow, did not already operate at a good level of service) are accounted for.

- *ASCT creates a statistically significant 17% reduction in total intersection crashes.* There is no statistically significant change in FI crashes, so mainly property damage only crashes are impacted. Safety effects tend to be more pronounced at sites with mainline AADTs over 30,000 vehicles per day. This again suggests that ASCT has the largest safety effect when some level of congestion is present at the site.

- *Feedback from the regions noted a number of institutional concerns that need to be accounted for prior to deploying the system.* The system relies on high-quality communications and vehicle detection, so regions must be prepared to maintain the system at a higher level than traditional TOD systems. The InSync system offered an ability to coordinate signals across controller platforms, which offered unique benefits when corridors crossed city/county lines.

RECOMMENDATIONS

1. *VDOT's TED and the VDOT regions should continue to deploy adaptive traffic signal systems in Virginia. As new locations are considered, the factors listed in the "Considerations for Future Deployment" section should be explicitly reviewed prior to programming installation of a project.* A traffic engineering guidance document outlining these factors/considerations should be generated and practices established to help the VDOT regions determine whether to deploy additional adaptive signal systems.

2. *Once at least 3 years of data are available for all pilot sites, VCTIR should re-examine the crash data to determine if the CMFs in this study were maintained over time.* This would be conducted as a technical assistance project in the future and reported to VDOT's TED.

3. *If adaptive traffic signal systems other than InSync are deployed in the future, VDOT's TED or the appropriate VDOT region should conduct additional limited pilot testing to ensure that the results of the deployment are consistent with the InSync results.* This has already occurred for a pilot test of the OPAC system in VDOT's Northern Region. These additional tests do not need to be as detailed as the InSync test, but they should confirm and document the benefits and costs of the system.

BENEFITS AND IMPLEMENTATION PLAN

The ASCT pilot test demonstrated that an adaptive traffic signal system can generate significant safety and operational benefits if deployed at an appropriate location. Installation of an adaptive signal system could reduce user delays, stops, and crashes. Given the benefits of adaptive systems that were demonstrated in this pilot project, several regions are currently planning additional installations of adaptive signal systems. Further support of the technology by VDOT's TED will encourage additional deployments.

Implementation of the findings of this research is currently underway. VDOT's TED is currently developing a guidance document in consultation with VCTIR that will help regions assess whether ASCT is appropriate for a specific site. Major topics covered in this guidance document include the following:

- traffic and geometric conditions of sites where ASCT is likely to generate operational benefits
- institutional and deployment considerations for ASCT deployment, such as maintenance and communications requirements
- performance metrics to assess ASCT impacts, including guidance on conducting before and after studies.

VDOT's State Traffic Engineer will disseminate the guidance document to the regions once it is finalized.

This study also further supports the arterial operations program being led by VDOT's TED. A broad goal of the arterial operations program is to improve monitoring, central control, and interoperability across the arterial network. ASCT systems advance that goal though improved arterial monitoring. As a next step, VCTIR is currently supporting the VDOT TED's efforts to examine central signal system software that will improve interoperability and control across the network.

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REFERENCES

American Association of State Highway and Transportation Officials. *Highway Safety Manual*. Washington, DC, 2010.

Anzek, M., Kavran, Z., and Badanjak, D. Adaptive Traffic Control as Function of Safety. *ITS World Congress Proceedings,* San Francisco, CA, 2005.

Cambridge Systematics and Texas Transportation Institute. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation*. Cambridge Systematics, Cambridge, MA, 2005.

DKS Associates. *Evaluation of an Adaptive Traffic Signal System: Crow Canyon Road and Bollinger Canyon Road in San Ramon, California*. Oakland, CA, 2010.

Dutta, U., Bodke, S., Dara, B., and Lynch, J. *Safety Evaluation of SCATS Control System*. MIOH UTC TS22p1-2 2010-Final. Michigan Department of Transportation, Lansing, 2010.

Federal Highway Administration. *Travel Time Reliability.* 2006. http://ops.fhwa.dot.gov/publications/tt_reliability/brochure/ttr_brochure.pdf. Accessed December 1, 2012.

Federal Highway Administration. Adaptive Signal Control. 2013. http://www.fhwa.dot.gov/everydaycounts/technology/adsc/. Accessed February 6, 2015.

Fontaine, M.D. *Executive Summary: Evaluation of INRIX Travel Time Data in Virginia. Technical Memorandum.* Virginia Center for Transportation Innovation and Research, Charlottesville, 2013.

Garber, N.J., and Rivera, G. *Safety Performance Functions for Intersections on Highways Maintained by the Virginia Department of Transportation.* VTRC 11-CR1. Virginia Transportation Research Council, Charlottesville, 2010.

Gartner, N.H., Pooran, F.K., and Andrews, C.M. Optimized Policies for Adaptive Control Strategy in Real-Time Traffic Adaptive Control Systems: Implementation and Field Testing. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1811*. Transportation Research Board of the National Academies, 2002, pp. 148-156.

Gettman, D., and Head, L. *Surrogate Safety Measures From Traffic Simulation Models.* FHWA-RD-03-050. Federal Highway Administration, Washington, DC, 2003.

Gettman, D., Pu, L., Sayed, T., and Shelby, S. *Surrogate Safety Assessment Model and Validation*. FHWA-HRT-08-051. Federal Highway Administration, Washington, DC, 2008.

Hauer, E. *Observational Before-After Studies in Road Safety*. Pergamon Press, Oxford, England, 1997.

Hicks, B., and Carter, M. *What Have We Learned About ITS: Arterial Management?* Federal Highway Administration, Washington, DC, 2000.

Hutton, J., Bokenkroger, C., and Meyer, M. *Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri*. Report 110637. Missouri Department of Transportation, Jefferson City, 2010.

INRIX. *INRIX XD Traffic: Fueling Future Mobility With Big Data.* No Date a. http://www.inrix.com/pdf/INRIXXDTrafficBackgrounder.pdf. Accessed December 3, 2013.

INRIX. INRIX XD™ Traffic Covers More Roads With Greater Precision Than Any Other Traffic Service. http://www.inrix.com/xdtraffic.asp#Accuracy. No Date b. Accessed December 3, 2013.

Institute of Transportation Engineers. *Traffic Engineering Handbook, 5th Edition*. Washington, DC, 1999.

Midenet, S., Saunier, N., and Boillot, F. Exposure to Lateral Collision in Signalized Intersections With Protected Left Turn Under Different Traffic Control Strategies. *Accident Analysis and Prevention*, Vol. 43, No. 6, November 2011, pp. 1968-1978.

Rhythm Engineering. The InSync Model. No Date a. http://rhythmtraffic.com/how-insync-works/the-insync-model/#local. Accessed February 6, 2015.

Rhythm Engineering. InSync's Performance. No Date b. http://rhythmtraffic.com/insyncs-performance/. Accessed October 3, 2012.

Sabra, Z.A., Gettman, D., Henry R.D., and Nallamothu, V. *Balancing Safety and Capacity in an Adaptive Signal Control System—Phase 1*. HRT-10-038. Federal Highway Administration, Washington, DC, 2010.

Sabra, Z.A., Gettman, D., Henry R.D., and Nallamothu, V. *Enhancing Safety and Capacity in an Adaptive Signal Control System—Phase 2*. FHWA-PROJ-10-0037, 2011-2013. Federal Highway Administration, Washington, DC, 2013.

Schrank, D., Eisele, B., and Lomax, T. *2012 Urban Mobility Report*. Texas A&M Transportation Institute, College Station, 2012.

Selinger, M. Hitting All the Greens: Signal Systems That React in Real Time More of a Reality. *Roads and Bridges,* Vol. 98, No. 1, January 2010, pp. 52-55.

Shetler, S. SCATS and InSync Adaptive Signal Systems: An Agency Perspective on Installation and Operations. Presentation to the 2012 NW Transportation Conference, Corvallis, OR, 2012. http://www.oregon.gov/ODOT/TD/TP_RES/docs/2012NWTC/2012NWTC_Presentations/33_SCATSandInSync.pdf. Accessed November 28, 2013.

Siromaskul, S., and Selinger, M. *InSync: The Next Generation of Adaptive Signal Systems.* Western ITE Annual Meeting, San Francisco, 2010. http://www.westernite.org/annualmeetings/sanfran10/Papers/Session%209_Papers/ITE%20Paper_9A-Siromaskul.pdf. Accessed October 2, 2012.

Sprague, D. *Adaptive Signal Timing: Comparison Between the InSync and QuicTrac Adaptive Signal Systems Installed in Colorado*. CDOT-2012-6. Colorado Department of Transportation, Denver, 2012.

Stevanovic, A. *Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*. NCHRP Synthesis 403. Transportation Research Board of the National Academies, Washington, DC, 2010.

Stevanovic, A., Kergaye, C., and Haigwood, J. *Assessment of Surrogate Safety Benefits of an Adaptive Traffic Control System*. 3rd International Conference on Road Safety and Simulation, Indianapolis, IN, September 14-16, 2011.

Transportation Research Board. *Highway Capacity Manual.* Washington, DC, 2010.

Virginia Department of Transportation. *Statewide Travel Time System: Business Rules and Standard Operating Procedures for Travel Time Dissemination on Dynamic Message Signs*. Richmond, 2010.

Virginia Department of Transportation. *Highway Safety Improvement Program (HSIP).* November 27, 2012. http://www.virginiadot.org/business/ted_app_pro.asp. Accessed February 10, 2015.